Energetic Phenomena III

N. Gopalswamy, NASA/GSFC

Topics:
Coronal Mass Ejections (CMEs)

Statistical and Physical properties
CME rates
Solar cycle variation of CME sources
Special populations
- Halo CMEs
- geoeffective CMEs
- Shock-driving CMEs

What are CMEs?

- Large-scale magnetized plasma ejected from the Sun (part of the corona is expelled with its magnetic field)
- Propagate into the interplanetary medium and impact planets in the solar system
- The driving forces are not well understood, but related to solar magnetic fields that help push coronal material out of solar gravitational potential well.

Why Study CMEs ?

Apart from the underlying physics,

- Long-term geoeffects: the severest of geomagnetic storms are due to CMEs (Tsurutani et al., 1990; Gosling et al., 1990)
- Long-lasting SEP events originate from CME-driven shocks (Reames, 1995)
- Energetic Storm Particles (ESPs) are carried by CME-driven IP shocks

→ Main player in the Sun-Earth connections

Prominences

- Prominence eruptions are integral parts of CMEs (Munro et al., 1979).
- Prominences were established in the late 1800's : Secchi (1872) had already classified the prominences into active and quiescent.
- Speeds of 100's of km/s were observed from spectroscopic observations (Fenyi 1892).
- Greaves and Newton (1928b) correctly suggested a relationship between prominence eruptions and geomagnetic storms, but Hale (1931) pointed out that they fell back and subsequently dismissed by Newton (1939) since PEs rarely attained escape velocity.
- In 1947, Payne-Scott discovered the type II radio bursts and suggested a connection to solar eruptions.
- Two classes of CMEs based on Inverse & Normal polarity filaments (Low and Zhang, 2002)?

Flares

- CMEs are almost always accompanied by flares in soft X-rays
- Following Carrington's white light flare (Carrington, 1860; Hodgson, 1859), the first two- ribbon flare was obtained by Young on 28 Sept 1870 (the drawing shows a large two-ribbon flare although he thought that they were prominences on the Sun.
- Hale's invention of the spectroheliograph to image the Sun and spectrohelioscope to identify rapid time variability and his vision to distribute his new instrument to various parts of the world began the patrol observations that started accumulating data on flares since 1934.
- Dellinger (1937): Sudden ionospheric disturbances were associated with flares (electromagnetic effect).
- How flares are related to CMEs is a topic of current research

CME History

- Mass Ejections known for a long time from Radio bursts, H-alpha observations (e.g, Payne-Scott et al., 1947).
- The concept of plasma ejection known to early solar terrestrial researchers (Lindeman, 1919; Chapman & Bartels, 1940; Morrison, 1954; Gold, 1955).
- CMEs as we know today were discovered in white light pictures obtained by OSO-7 spacecraft (Tousey, 1973).
- OSO-7, Skylab, P78-1, SMM and SOHO missions from space, and MLSO from ground have accumulated data on thousands of CMEs.
- CME properties are measured in situ by many spacecraft

A 19th Century CME in Eclipse Data

Eddy (1974)

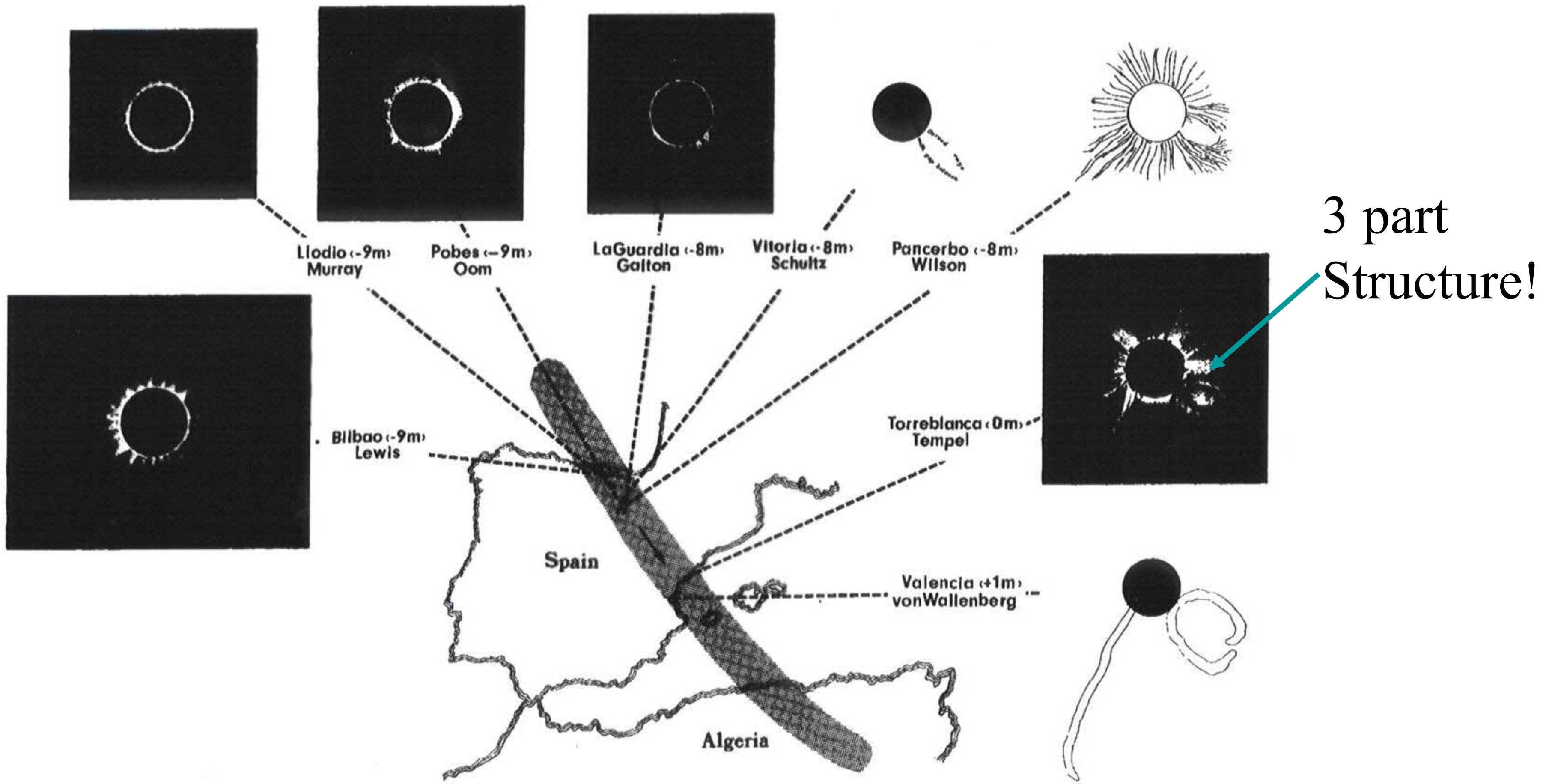
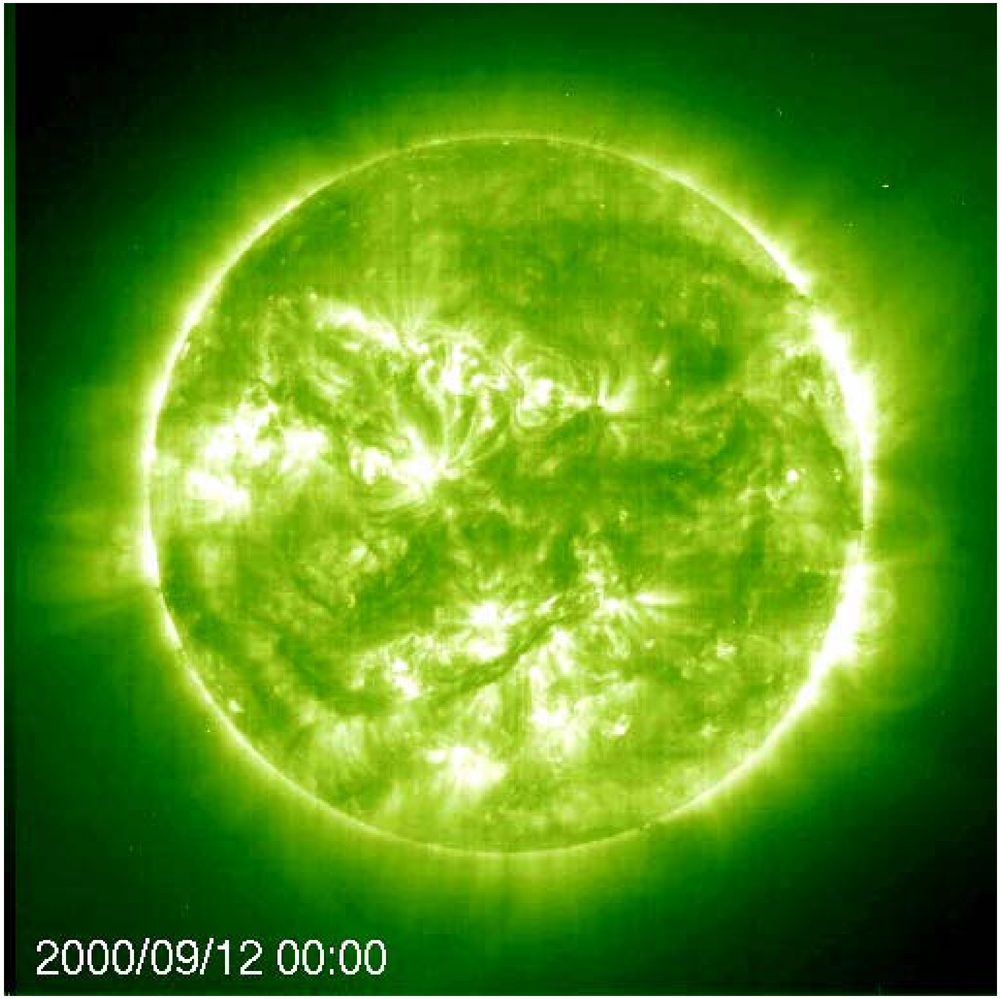


Fig. 4. Selected drawings of the corona (from Ranyard, 1879), made by different observers along the path of totality in Spain during the 1860 eclipse. Times are relative to mid-totality at Tempel's station at Torreblanca

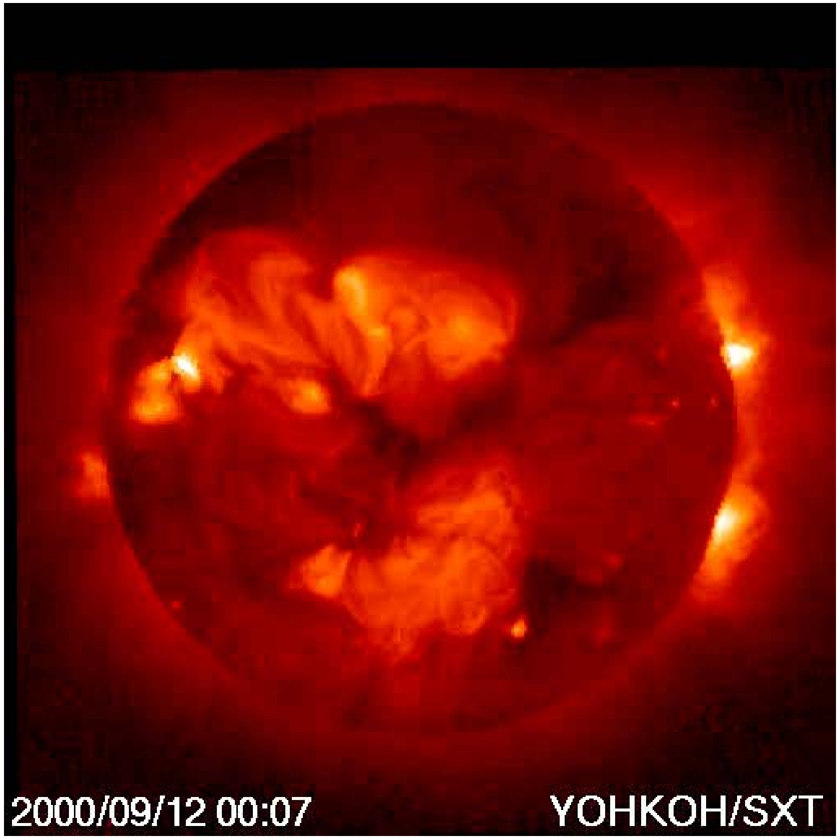
July 18 1860

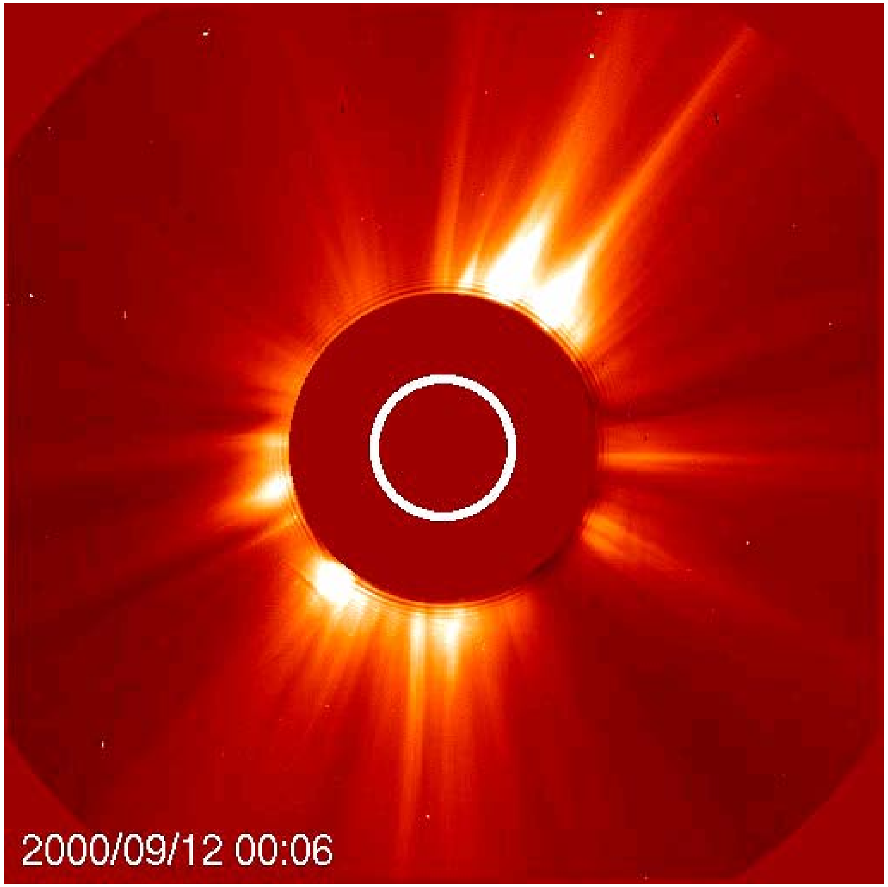
Filament Eruption in EUV

- SOHO/EIT (195 A) images presented as a movie.
- The NW-SE filament (seen in H-alpha in the previous slide) erupts and becomes the core of the white light CME.
- Arcade formation follows the eruption.



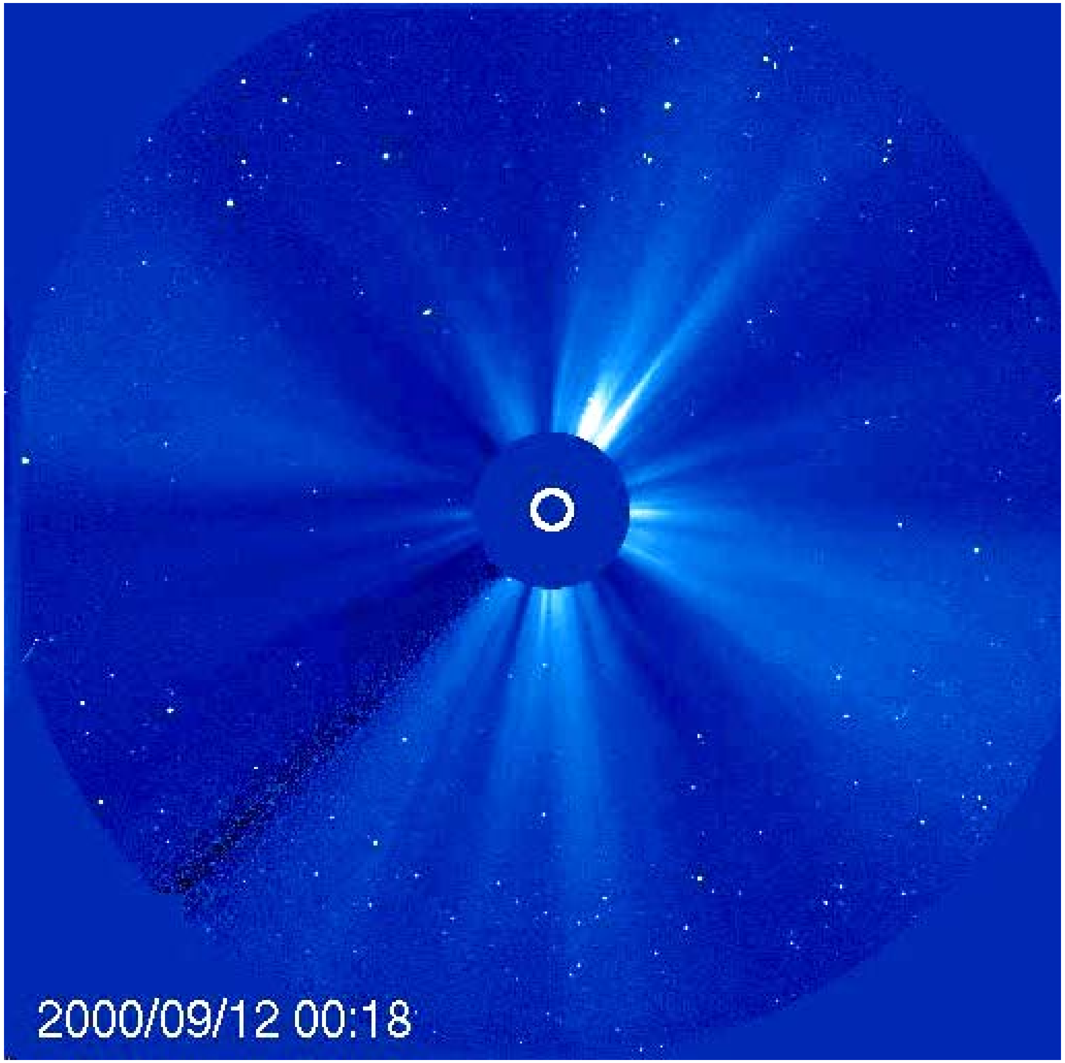
2000/09/12 CME source in soft X-rays



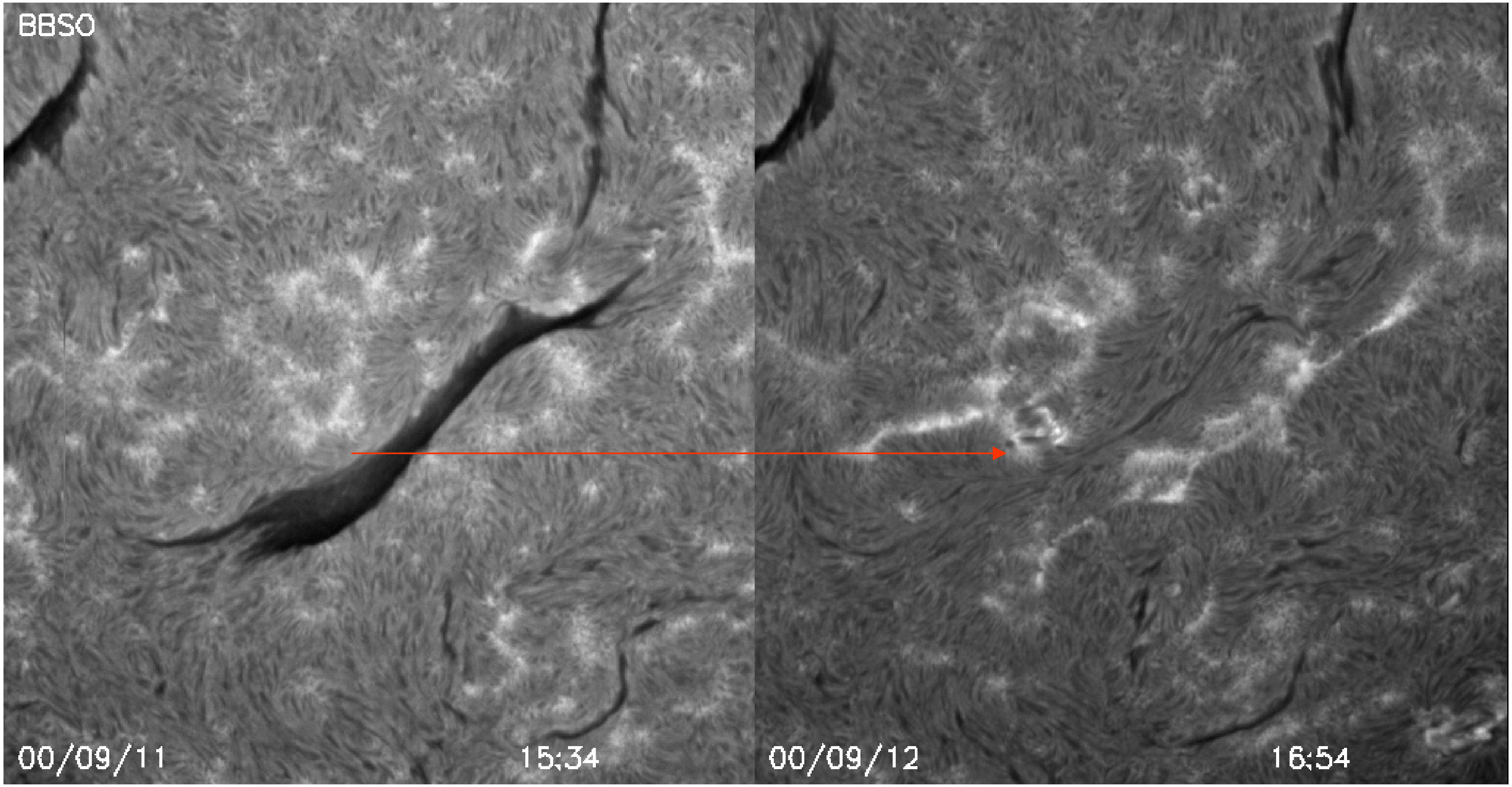


2000/09/12 CME in the outer corona/IP medium

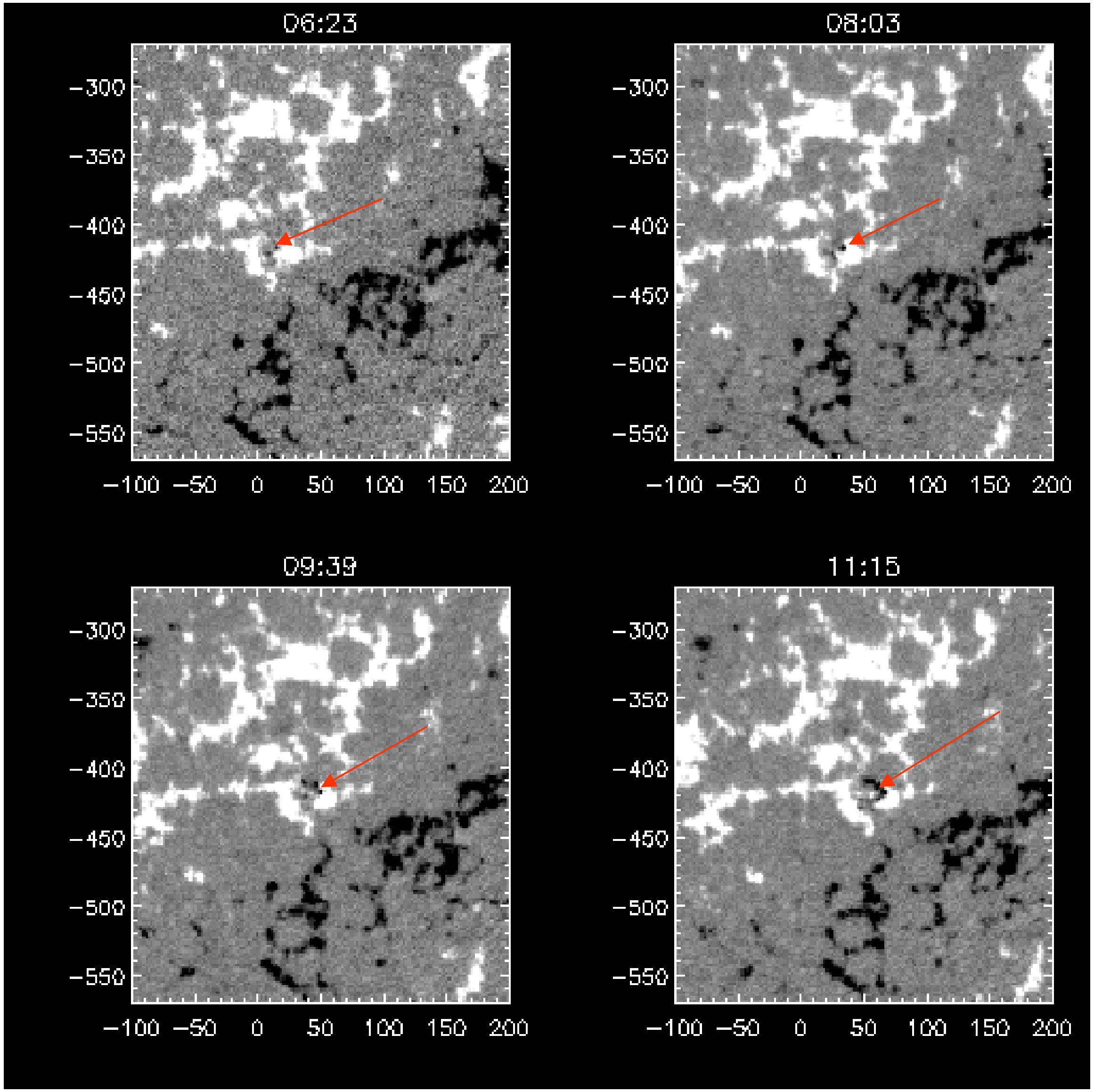
- SOHO/LASCO C3 movie
- Partial halo event consistent with the southern location on the disk
- The bright core is the filament that was dark in the previous movie



H-alpha: Before and After Eruption

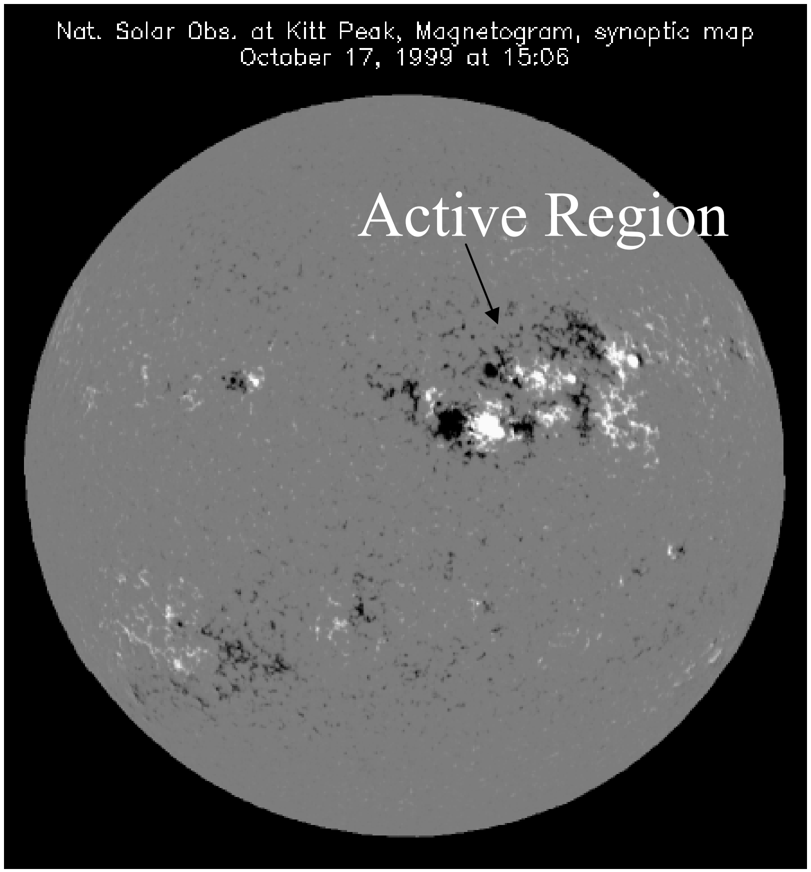


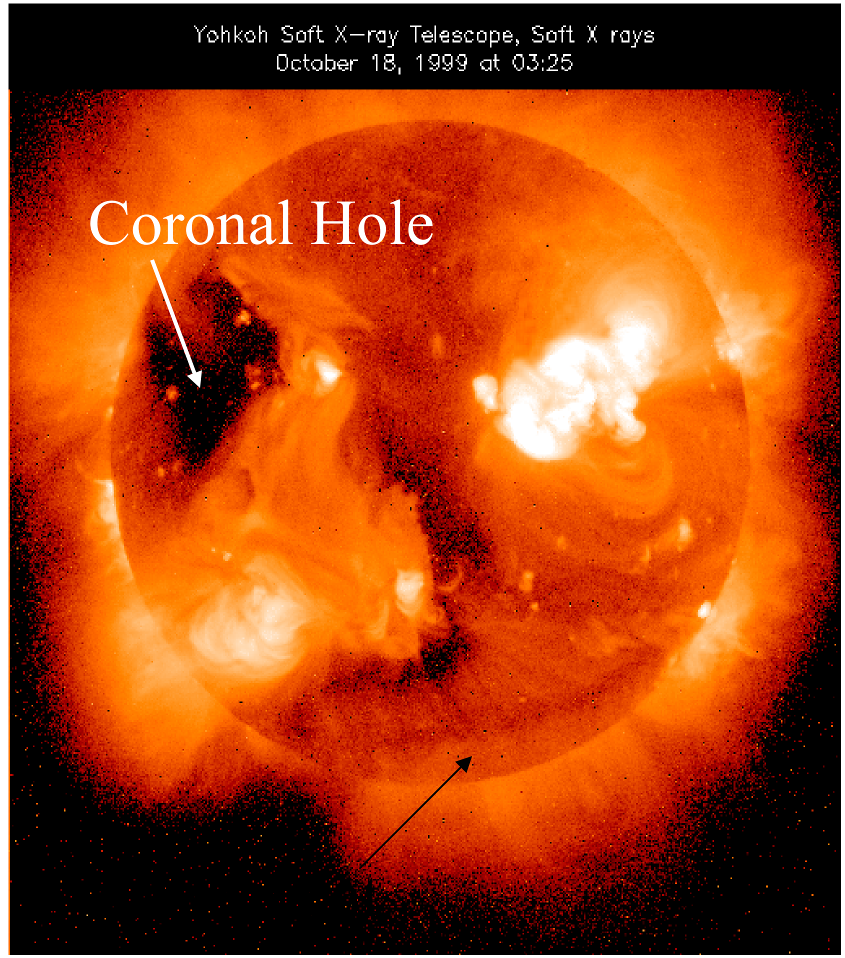
"Reconnection-favoring" Flux Emergence"



Closed and Open Magnetic Regions on the Sun

Closed field region

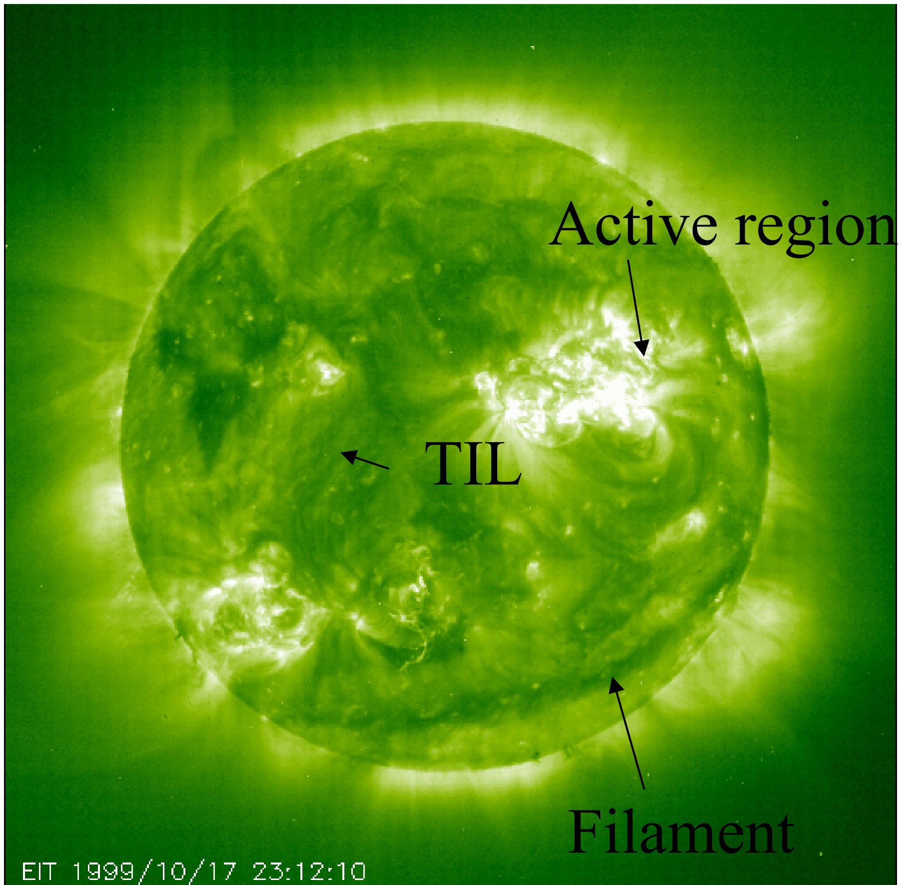




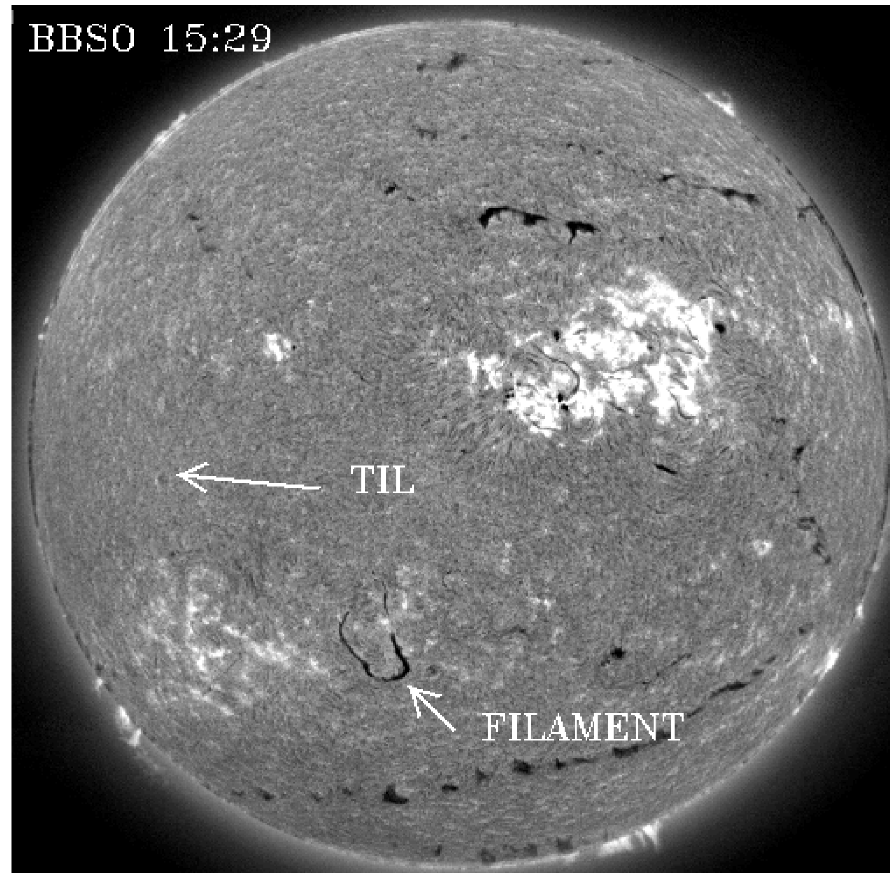
Open field region

Examples of Closed Field Regions

SOHO/EIT image 195 A



H-alpha picture



Where do CMEs originate?

- CMEs originate from closed field regions

- Active Regions
- Filament regions
- Combination of AR and Filament regions
- Transequatorial interconnecting regions (Gopalswamy et al. 1999, solar wind 10)

- CMEs do not originate from coronal holes!

- Filaments near coronal holes show a proclivity for eruption (Webb et al., 1978; Bhatnagar, 1996)

CME Detection

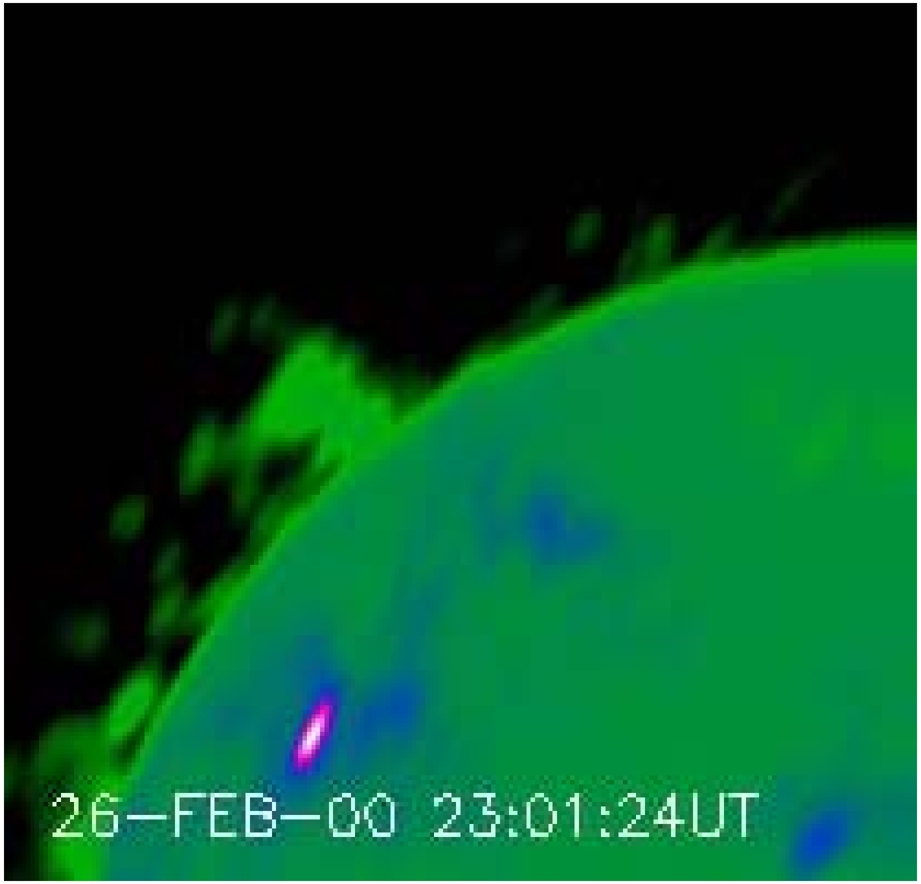
- White light: Thomson scattering of photospheric light; Need occulting disk to block photospheric light (million times brighter than the corona). Samples mass irrespective of T.
- Other wavelengths: Near-surface (H-alpha, X-ray, EUV, Radio) and IP manifestations (Radio, white light, IPS, *In situ*). T, n, B dependent.
- Mostly thermal emission (continuum, line). In radio thermal and nonthermal emissions (trillion K brightness temperature possible)

Consequences of CMEs

- Drive shocks (SEPs, ESPs, Radio bursts, SSC, GLEs)
- (Ozone depletion, Cloud cover change)
- Induce Flares (SID, impulsive SEPs)
- Geomagnetic Storms: frontside halos
- (Forbush decrease)

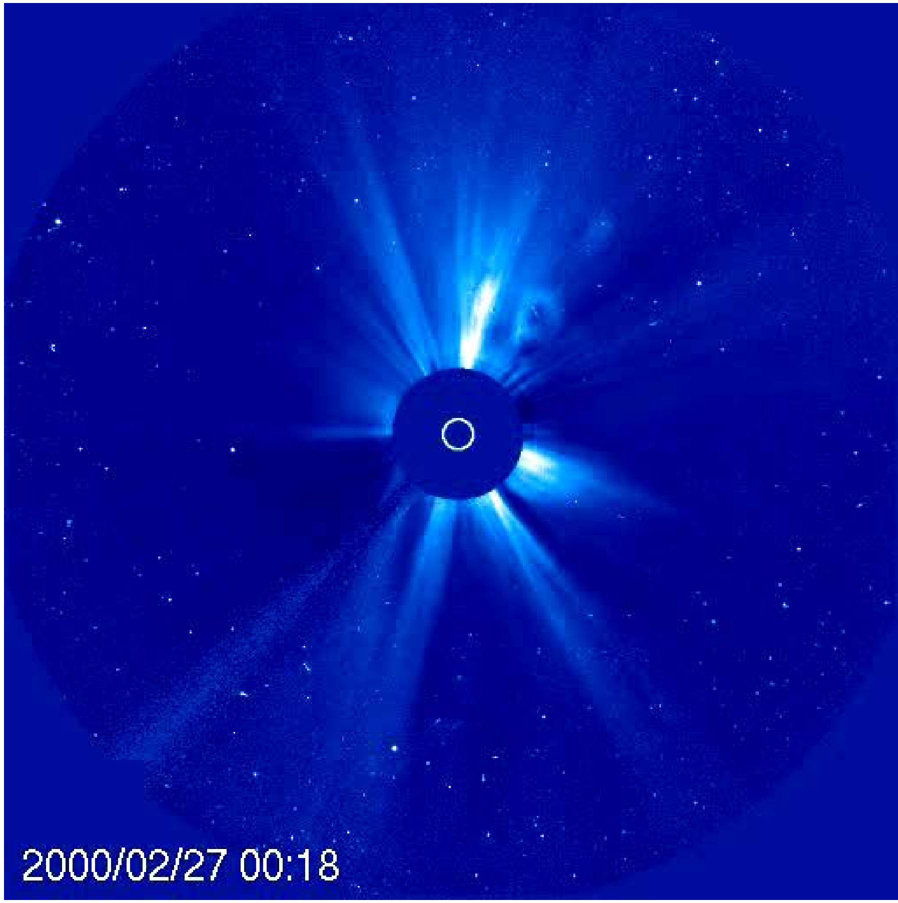
What is a CME?

A prominence eruption that becomes CME core (in microwaves, Nobeyama)



Brightening on the disk is the associated flare

SOHO/LASCO sees the CME Later in the corona with the core



Basic Attributes of a CME:
Speed, Width & CPA

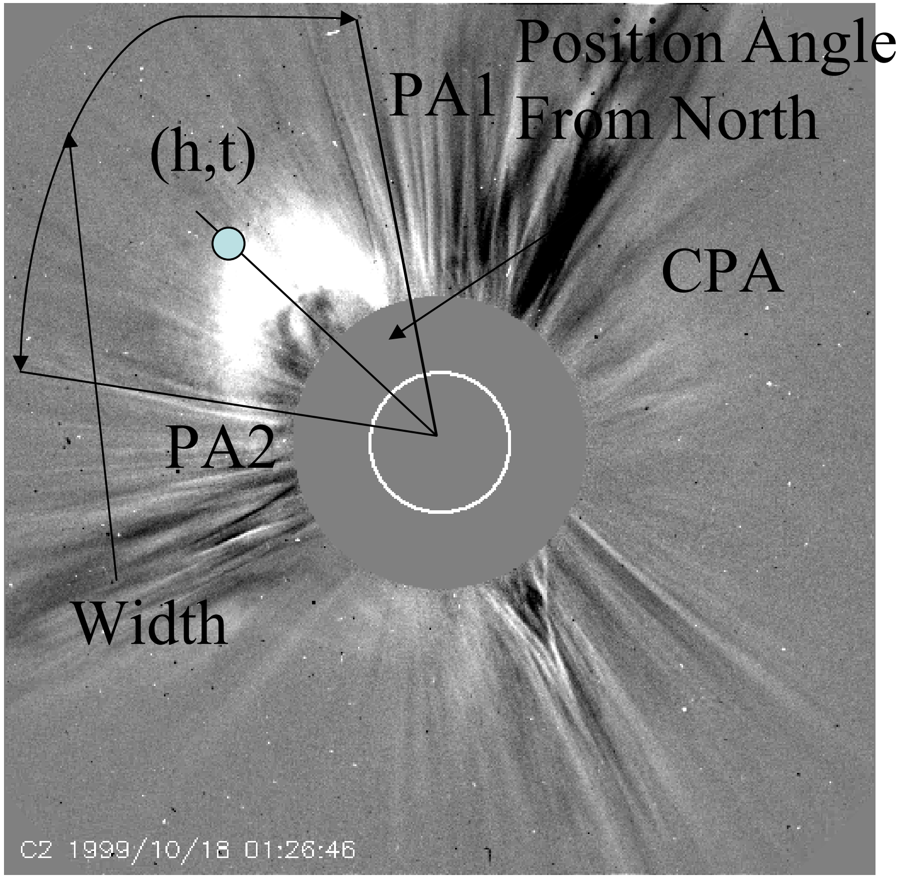
Base Difference: $F_n - F_o$
Running Difference: $F_n - F_{n-1}$
Fn, Fn-1, Fo are images at times t_n , t_{n-1} and t_o

CPA = Angle made by CME apex with solar North

Width = PA2 – PA1

Speed = dh/dt

N

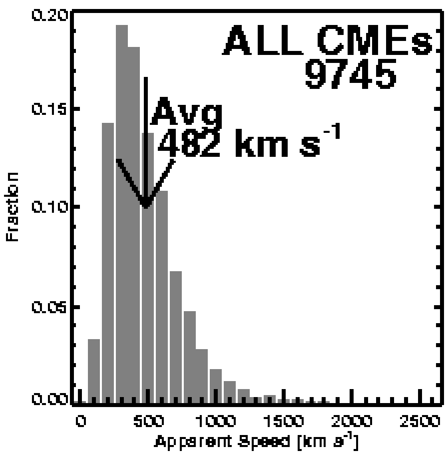


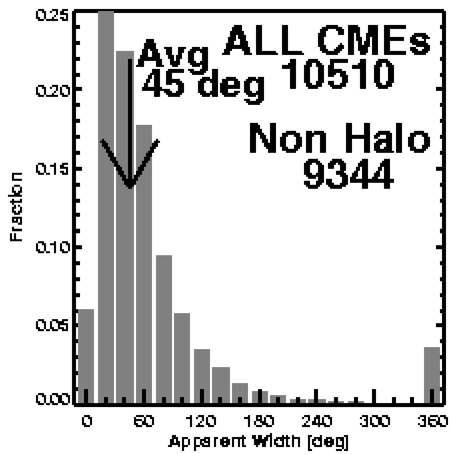
W

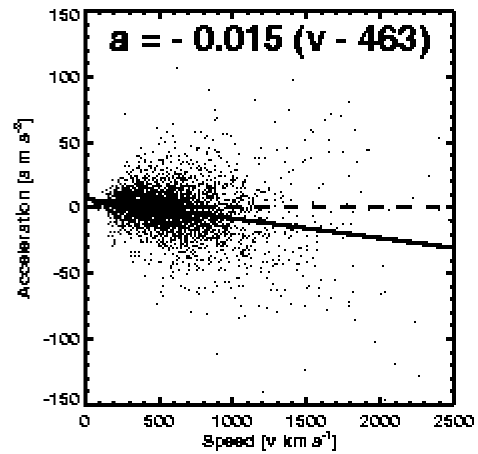
S

Statistical Properties

Gopalswamy, 2004



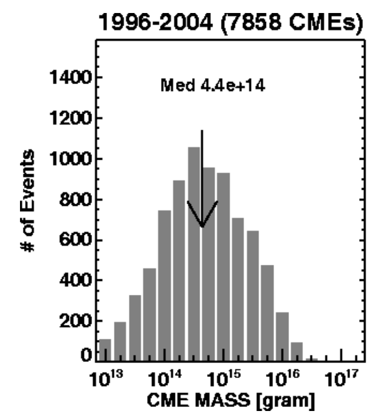


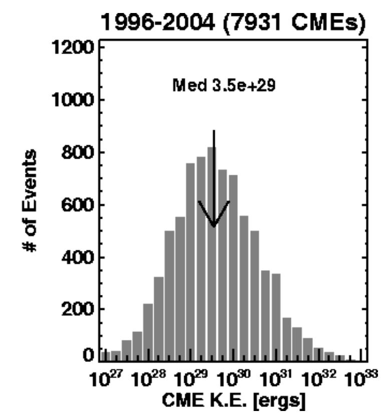


CME acceleration *a* depends on speed

a = 0 when *v* = 463, a crude estimate of solar wind speed

- The number of SOHO CMEs is an order of magnitude higher than that of pre-SOHO CMEs
- The average speed and width (of non-halo CMEs) are similar to pre-SOHO values
- The highest speed observed increased significantly to 3347 km/s, but the fraction of CMEs with V > 2500 km/s is tiny (10^{-4})
- The number of halo CMEs is significantly larger (~3%)
- Statistically, faster CMEs decelerate
- The average mass of SOHO CMEs is smaller than pre-SOHO values (due to SOHO's better dynamic range)





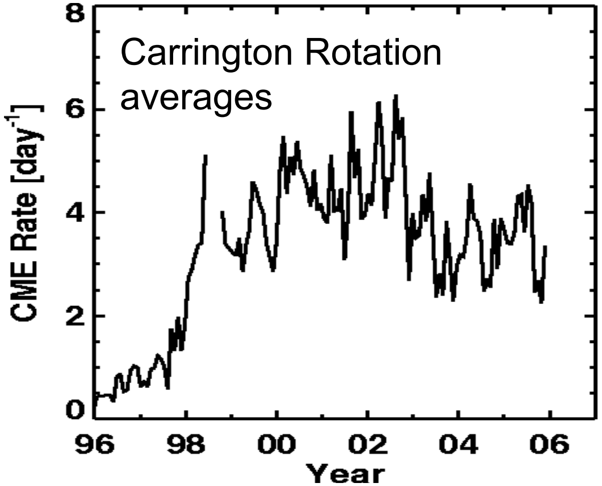
SOHO observed more low-mass CMEs resulting in a smaller average mass

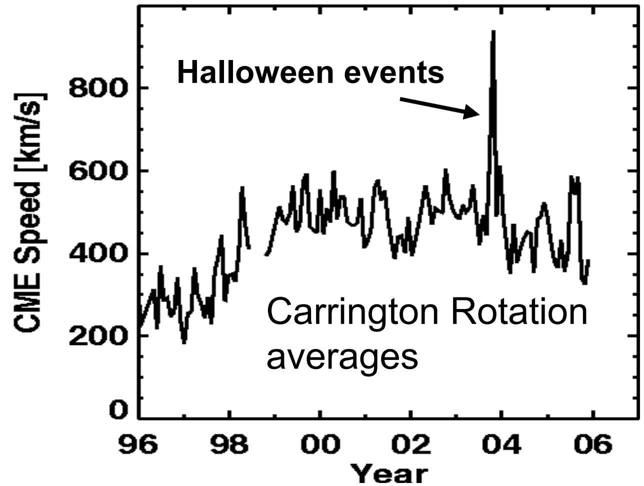
SOHO and Pre-SOHO CMEs

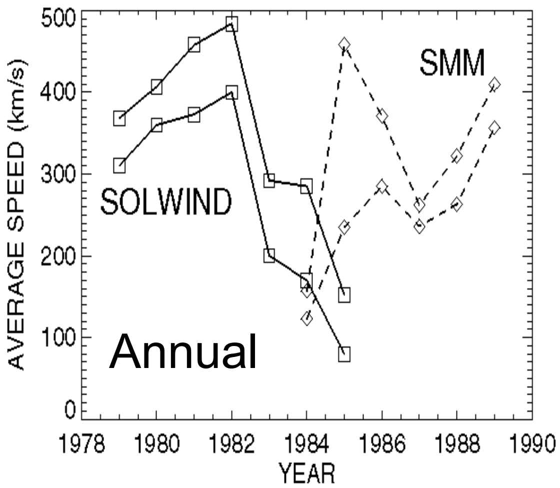
Coronagraph Epoch →	OSO-7 1971	Skylab 1973-74	Solwind 1979-85	SMM 1980,84-89	LASCO 1996-2005
FOV(Ro)	2.5-10	1.5 - 6	3 - 10	1.6 -6	1.2-32
#CMEs	27	115	1607	1206	10500
Mean V (km/s)	---	470	460	350	482
Mean W (deg.)	---	42	43	47	45
Mass (10^{15} g)	---	6.2	4.1	3.3	0.4
Reference	1	2	3	4	5

1 Tousey (1973)
2 MacQueen et al 1974
3 Michels et al 1980
4 Brueckner et al., 1995; Gopalswamy 2004

Solar Cycle Variation of CME Rate and Speed



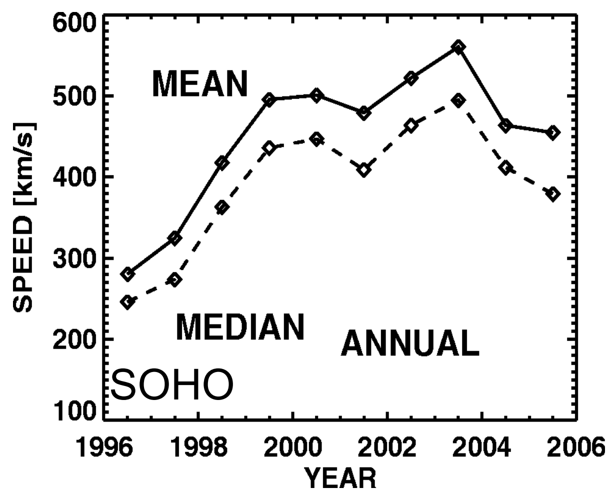




SOHO CME rate increased from ~0.5/day during solar minimum to ~6/day during maximum. The maximum rate is higher by a factor of 2 (pre-SOHO max rate ~3/day)

The pre-SOHO correlation between sunspot number and CME rate was confirmed, but the correlation was weaker. This seems to be due to the high-latitude CMEs that started in 1999 from polar crown filament region

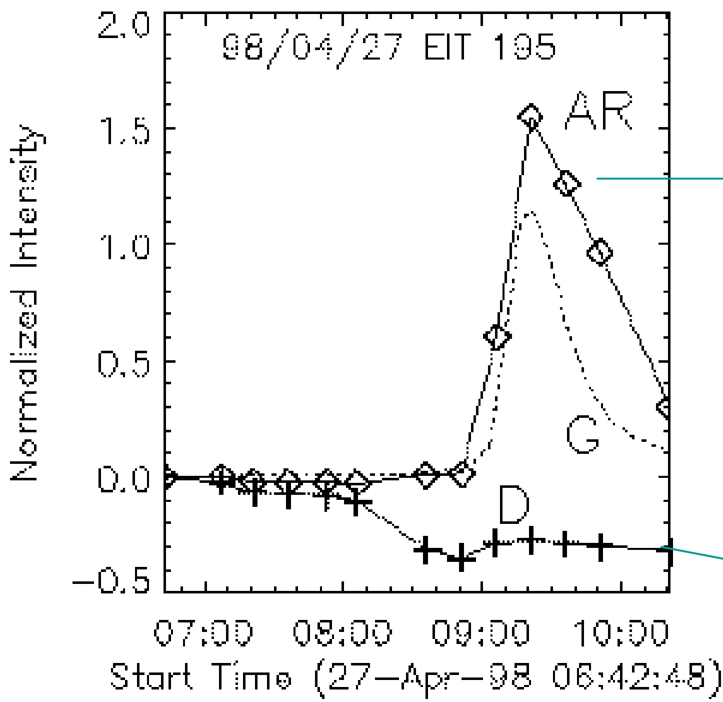
The solar cycle variation of average CME speed was inconclusive in the pre-SOHO era. SOHO data confirmed the increase from minimum to maximum by a factor of 2. The spikes in the speeds are due to some active regions, which are copious producers of fast CMEs.

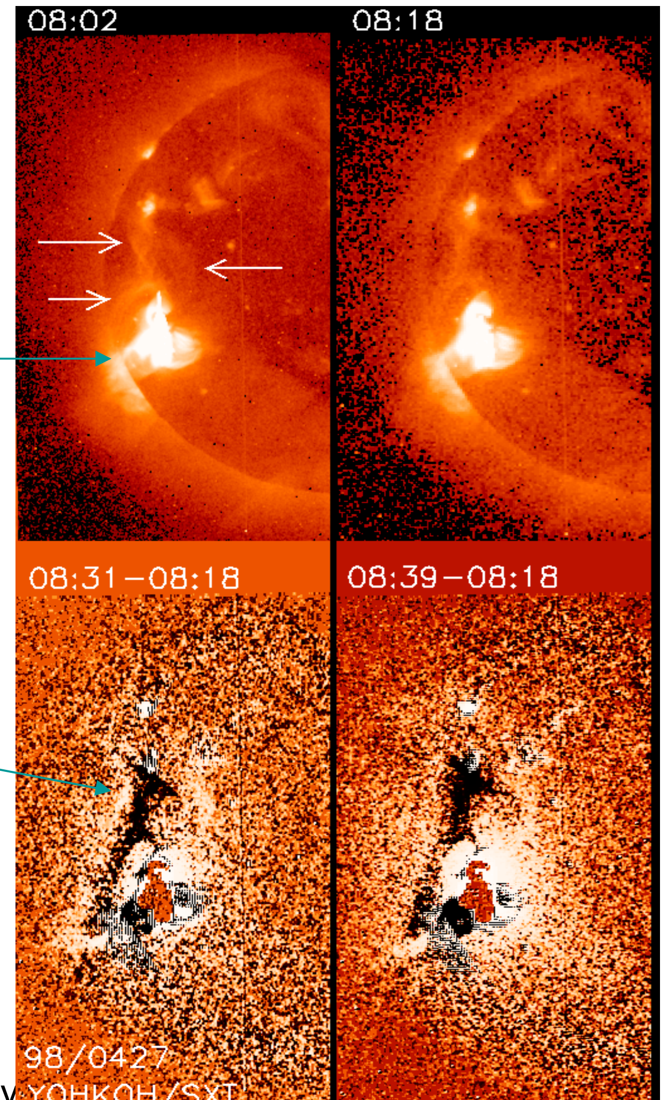


Pre-eruption Evolution: Prolonged Dimming

- Weak, prolonged dimming for ~ 1 hr (Gopalswamy et al., 1999)
- Small-scale opening of field lines resulting in the eruption of underlying structure? (Antiochos et al., 1994; Low and Zhang, 2002)

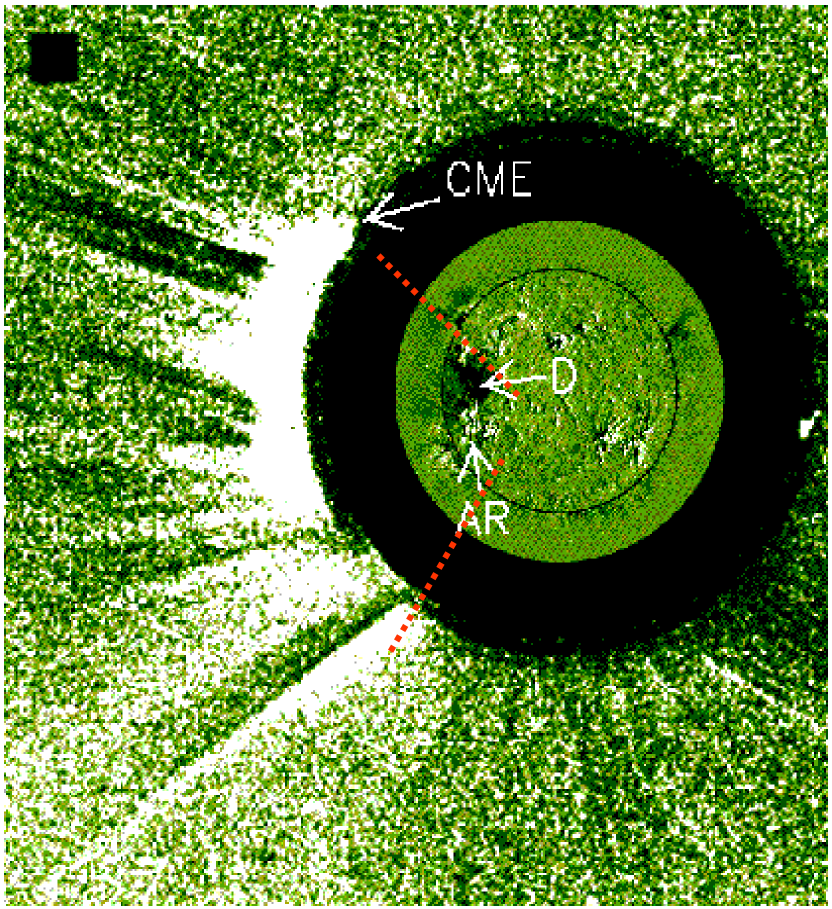
Weak Dimming Before Eruption





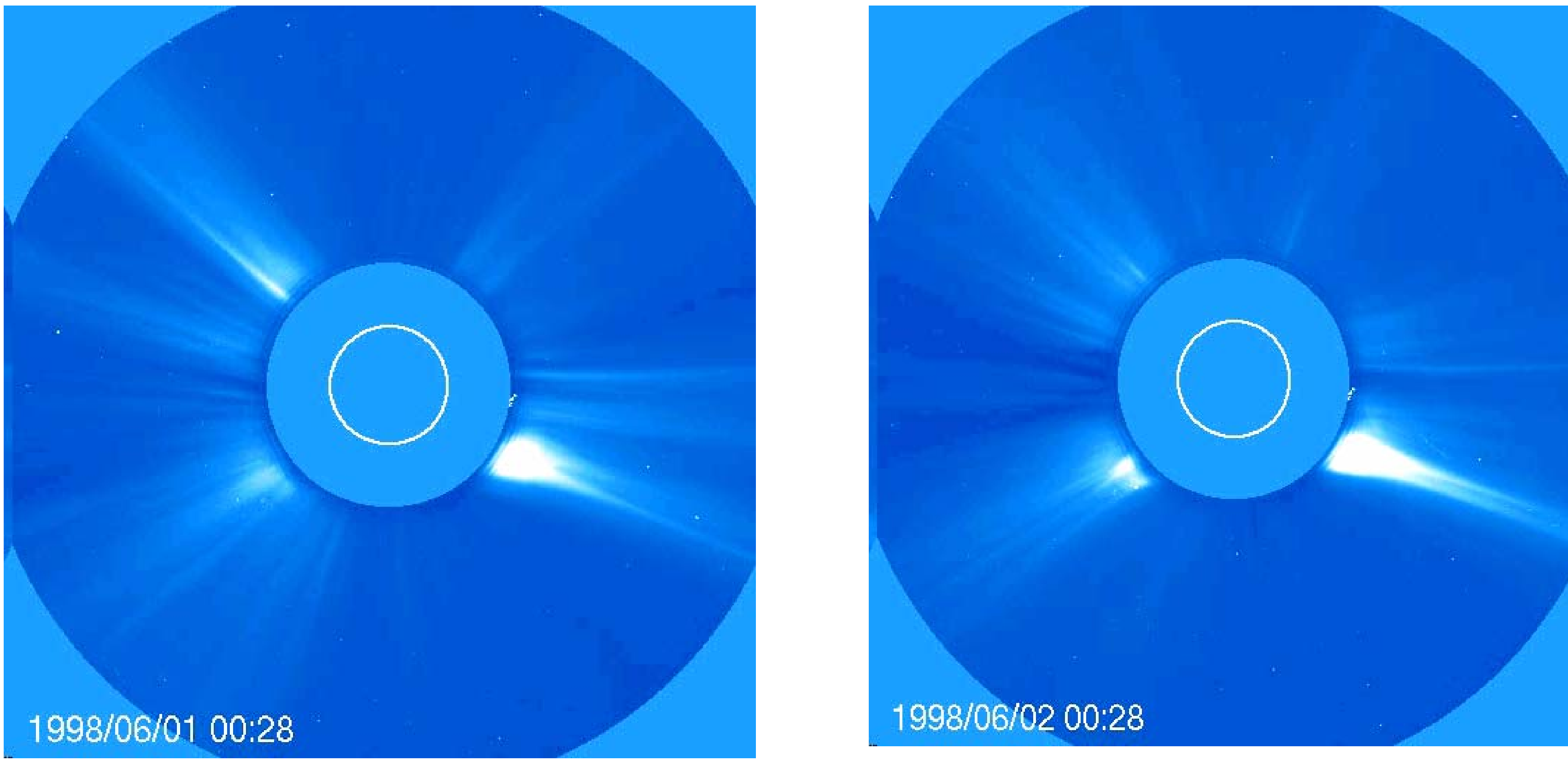
AR-Active Region D-Dimming
G-GOES X-ray Flux

A transequatorial Eruption



- EIT 195 A difference image showing dimming at 08:36 UT
- LASCO image at 08:56 UT

Streamer Distension & Eruption



Pre-eruption Energy Release

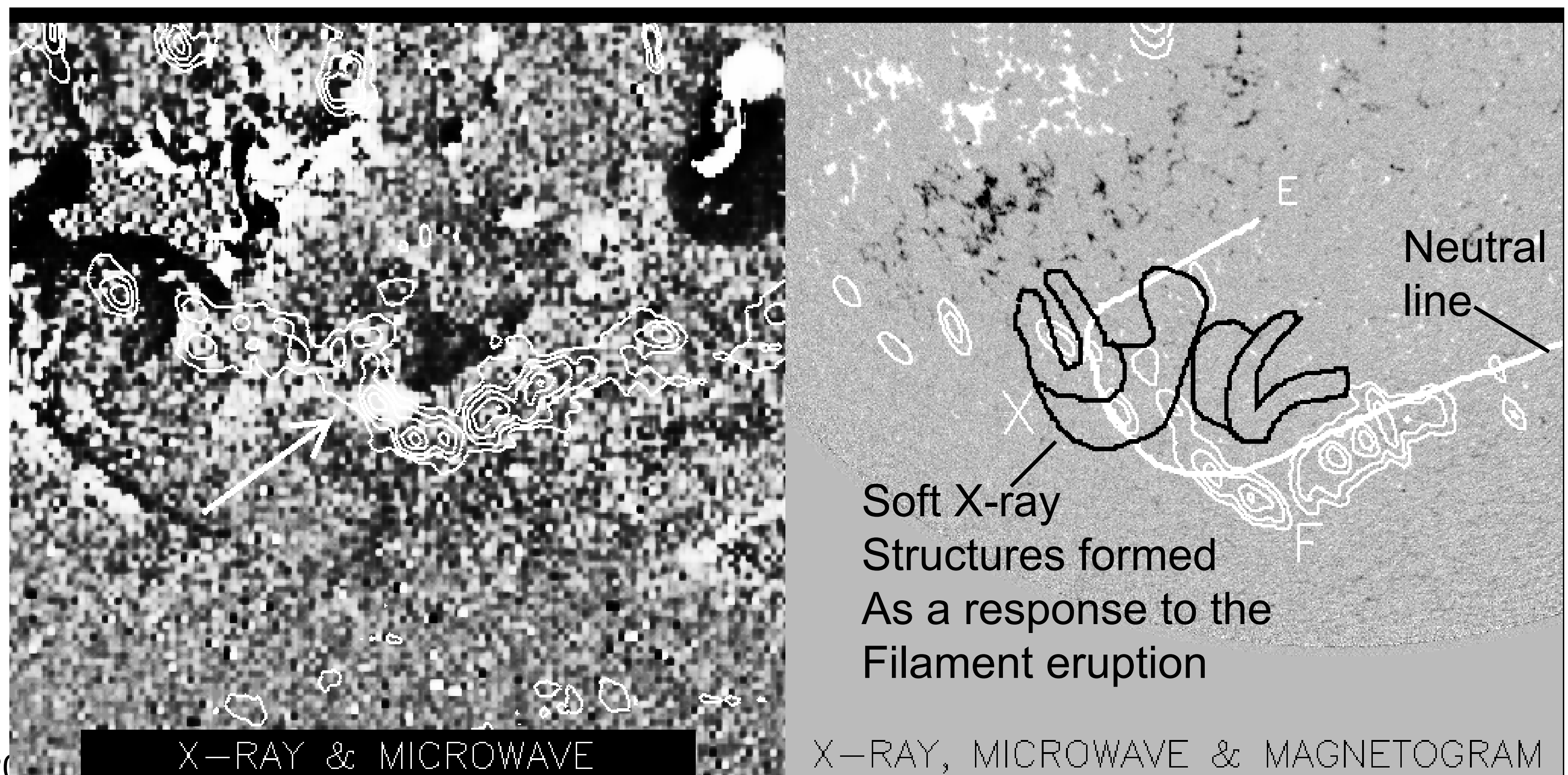
Pre-eruption Energy Release

- Signatures of pre-eruption energy release
- Small-scale heating near filaments, consistent with reconnection scenario (Feynman and Martin, 1995)
- Radio bursts near filaments – nonthermal energy release due to reconnection (Jackson et al., 1978; Marque, 2001- Nancay Observations)

Filament Eruption Onset

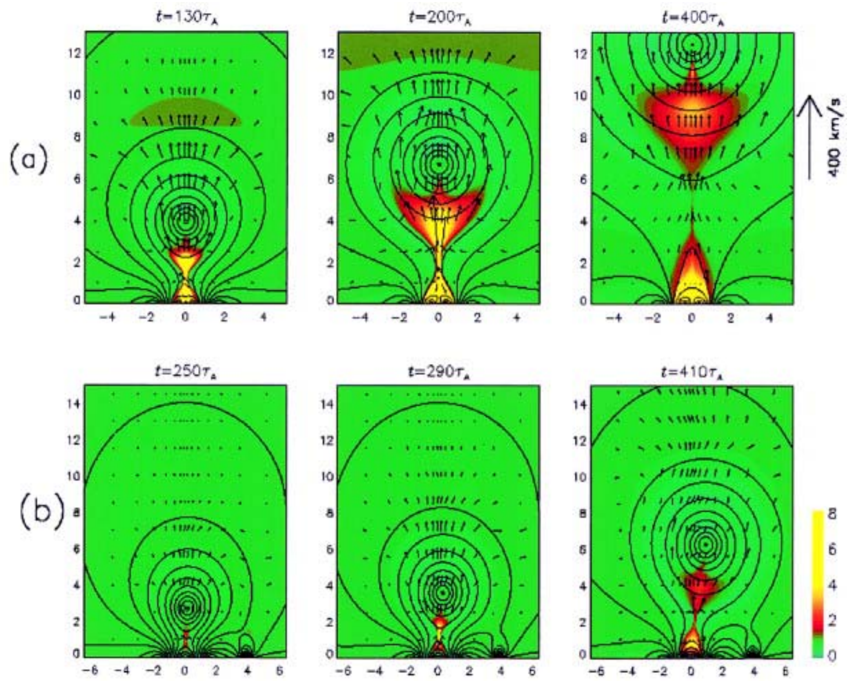
Soft X-ray brightening at the location where the filament (F) starts lifting. Filament in contours.

Gopalswamy, 1999



Pre-eruption Reconnection

- Top: Flux emergence under the filament
- Bottom: flux emergence from the side



(Chen & Shibata 2000)

Summary of Numerical Models of CME Initiation

Gopalswamy, 2003

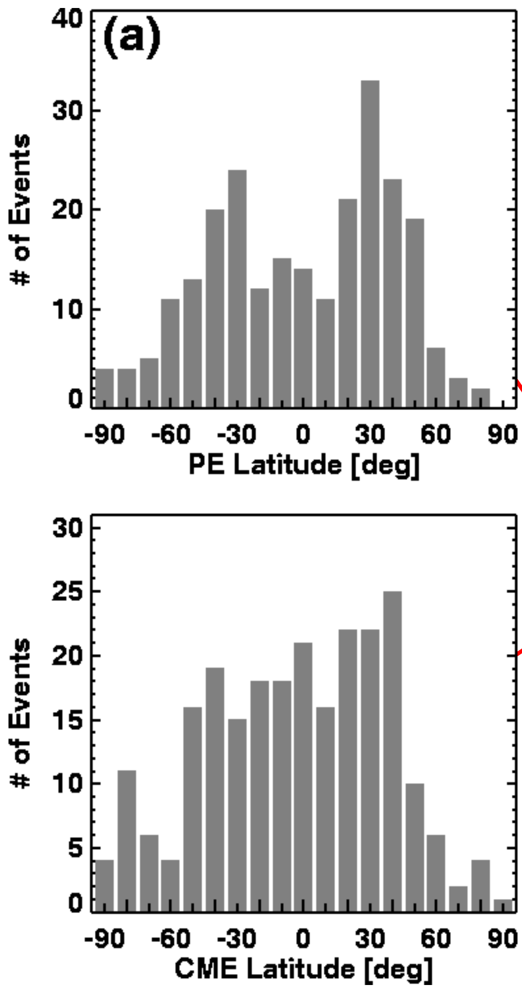
Model	Pre-Eruption Structure	Pre-eruption Evolution	Pre-eruption Energy Release
Forbes et al., 1994, Linker, et al. 2001	Flux rope in bipolar field: either emerges or forms in the corona	Flux decrease/changes leading to loss of equilibrium	None
Chen and Shibata, 2000	Flux rope in multipolar field	Flux emerges consistent with reconnection	Reconnection energization at the site of emergence
Antiochos et al., 1994	Sheared arcade in multipolar field	Continued shearing	Reconnection energization at coronal null/separator
Wu et al., 2000	Flux rope with overlying streamer in the solar wind	Increase in the azimuthal flux or shear of the streamer field	None
Chen et al., 1997	Flux rope in equilibrium	Increase in the azimuthal flux	None

Caution: This table is incomplete, mainly initiation

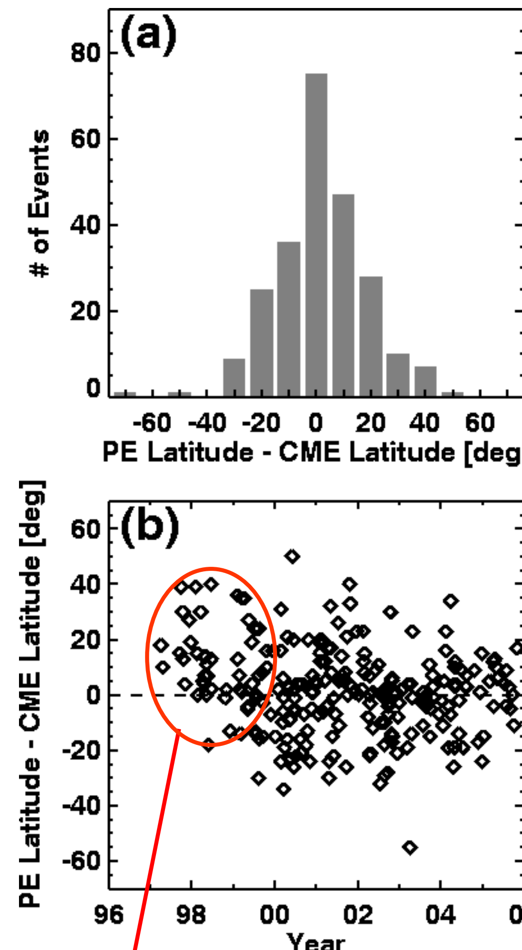
Prominence Connection & High-latitude CMEs

CMEs and Prominence Eruptions

Gopalswamy et al. 2003 ApJ



- Prominence eruptions from Nobeyama radioheliograph and SOHO CMEs confirmed the high-degree (83%) of association between CMEs and (PEs)
- CMEless PEs were much slower (20 km/s), attained very low heights and mostly moving horizontally.
- North-south asymmetry in CME and PE rate
- The latitude distributions of CMEs & PEs were different because of non-radial motion of CMEs during solar minimum

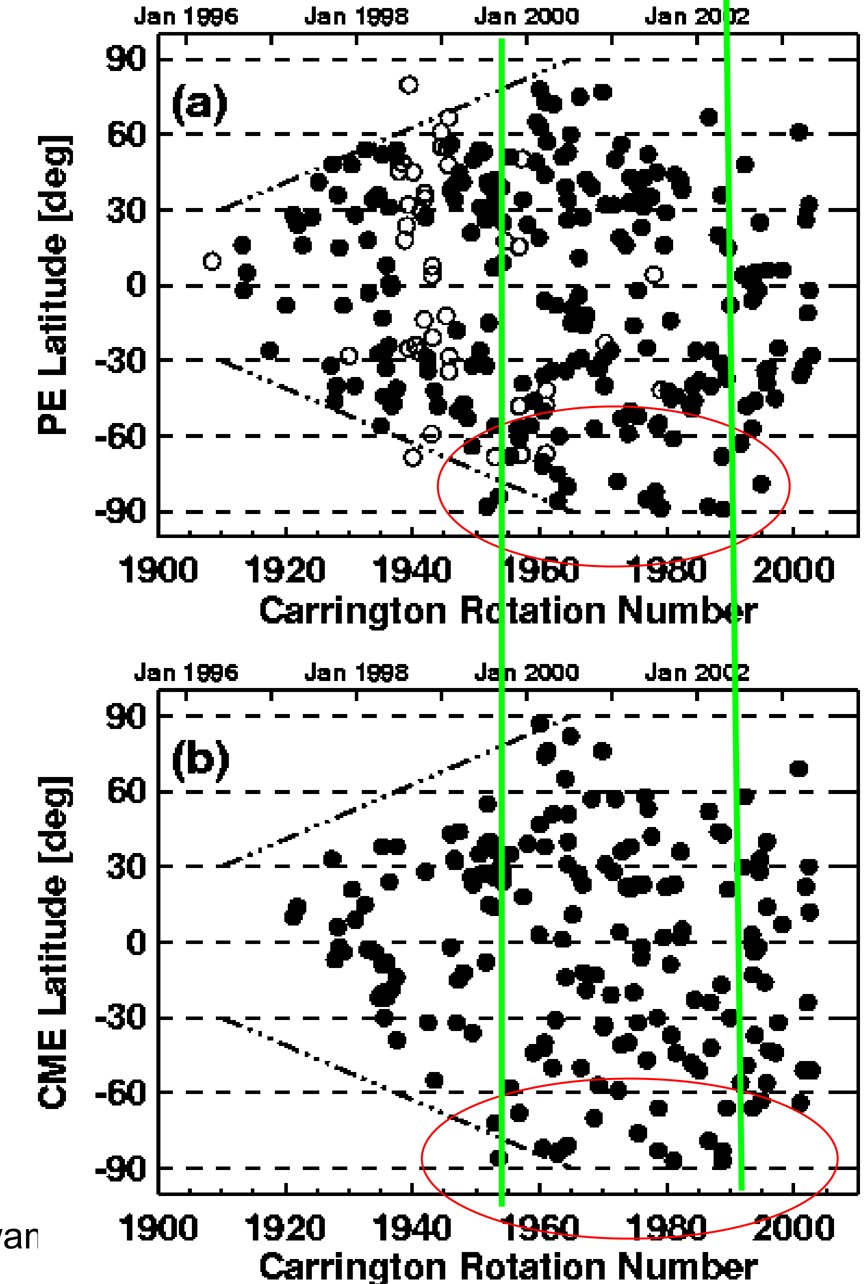


PE latitudes are closer to the poles than CME latitudes during solar minimum

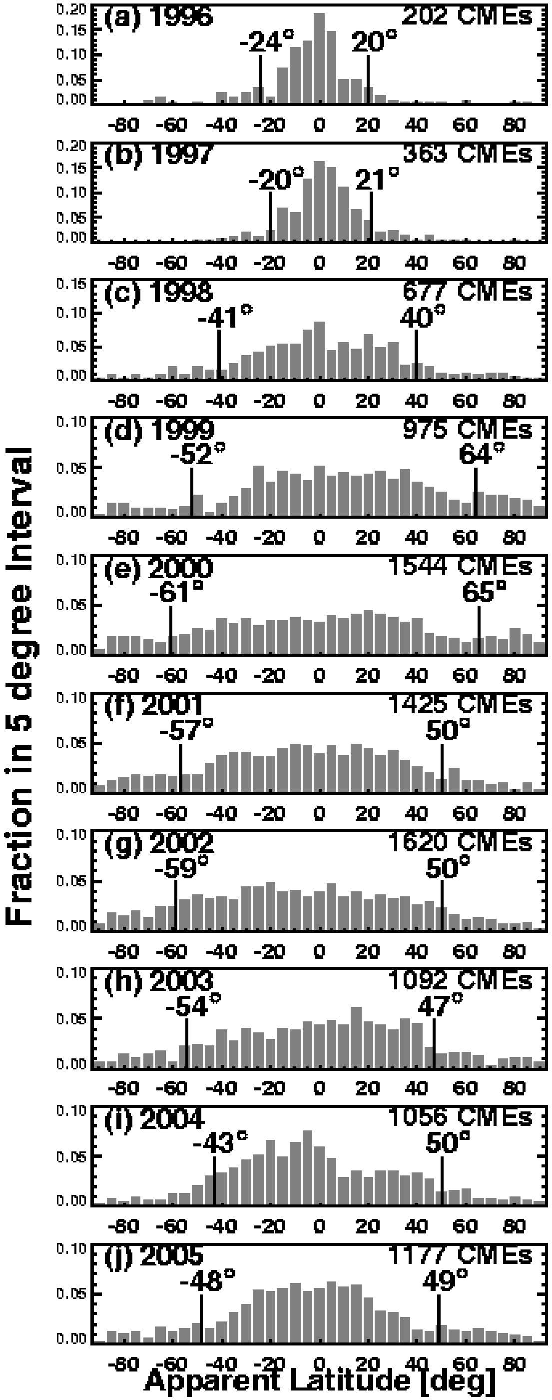
High-latitude CMEs

- High latitude prominence eruptions and CMEs during CR 1950-1990 (mid '99 – early '02)
- N-S asymmetry
- These CMEs are not associated with sunspot activity

- hence the poor correlation between CME rate & SSN



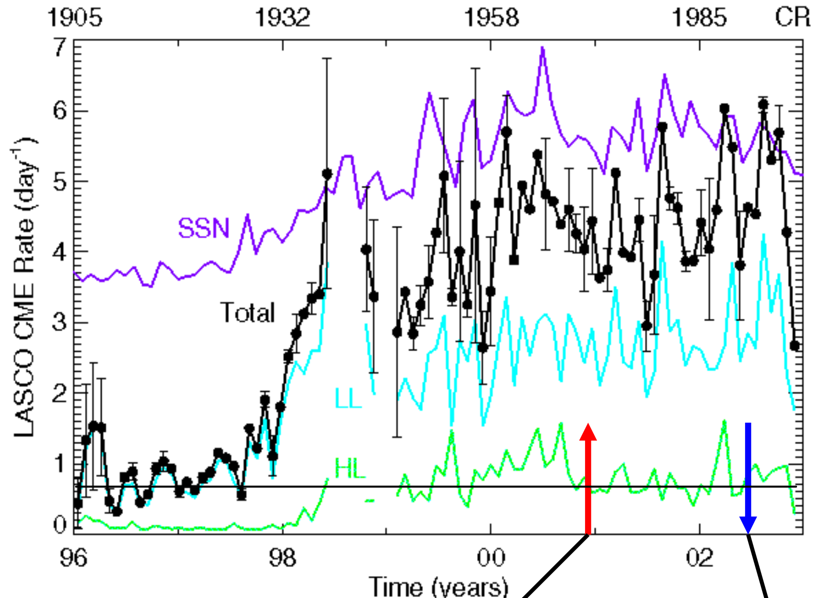
High & Low latitude CMEs



The average latitude changes significantly over the solar cycle

2005 distribution looks similar to that in 1998

HL: $|\lambda| \geq 60$ LL: $|\lambda| \leq 40$



Polarity reversal in the northern hemisphere

Polarity reversal in the southern hemisphere

Polarity reversal coincides with the cessation of HL CMEs separately in the northern and southern hemispheres

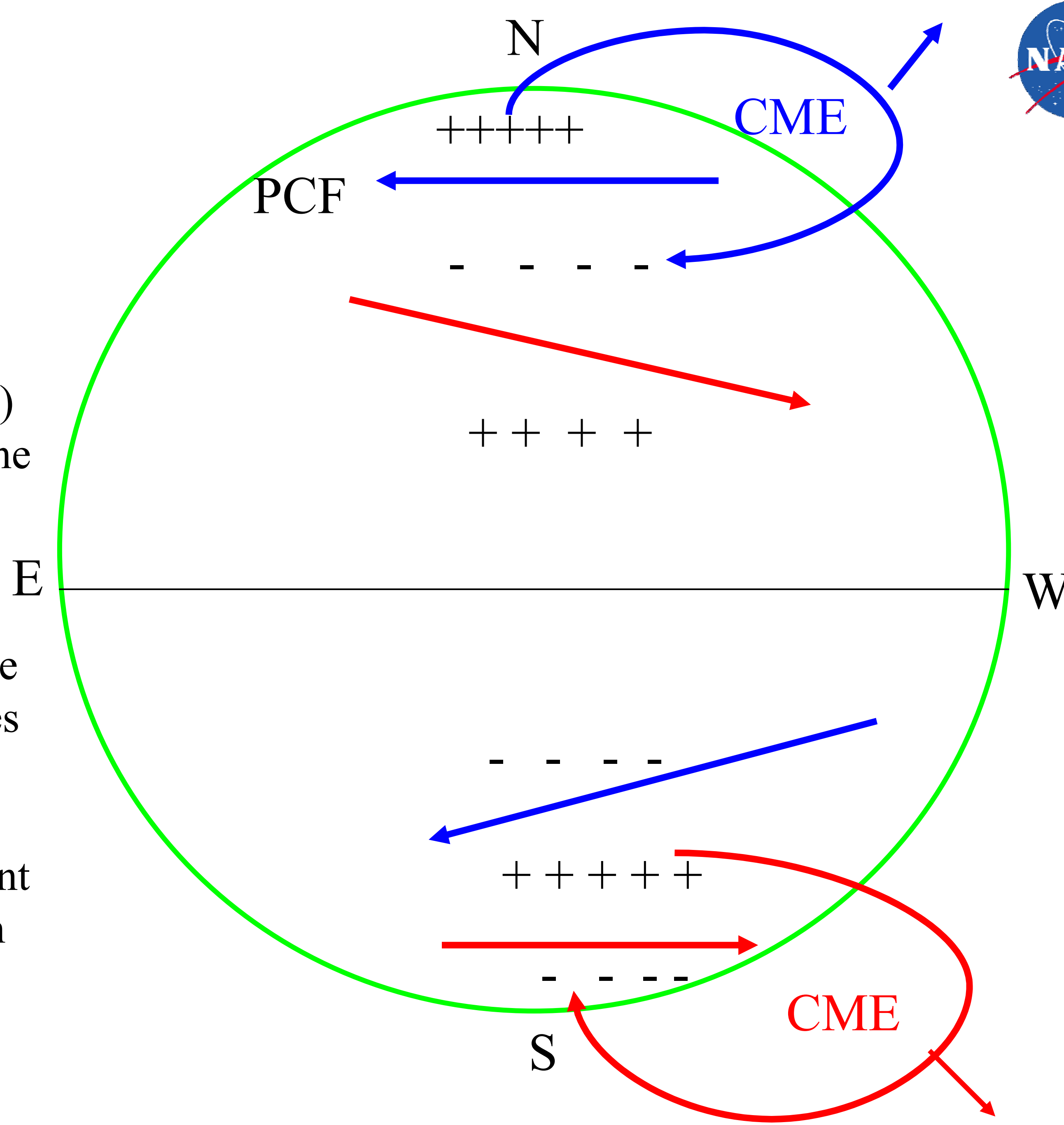
N. Gopalswamy

Solar magnetic filed pattern before reversal

The blue structures (Magnetic field in the polar crown filaments) must be replaced by the red for reversal in the north.

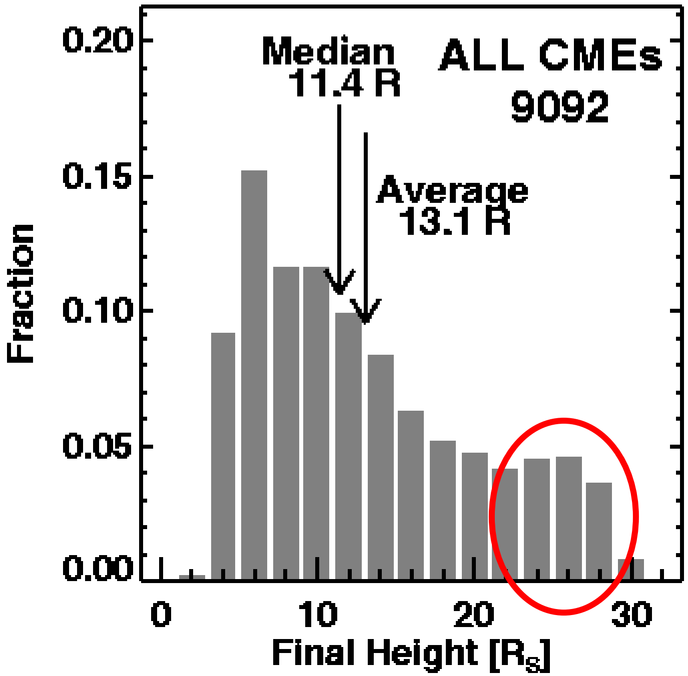
This happens when the high-latitude structures disappear as CMEs

The red fields represent the future polar crown filament in the north



CMEs Affecting the Heliosphere

Gopalswamy, 2004

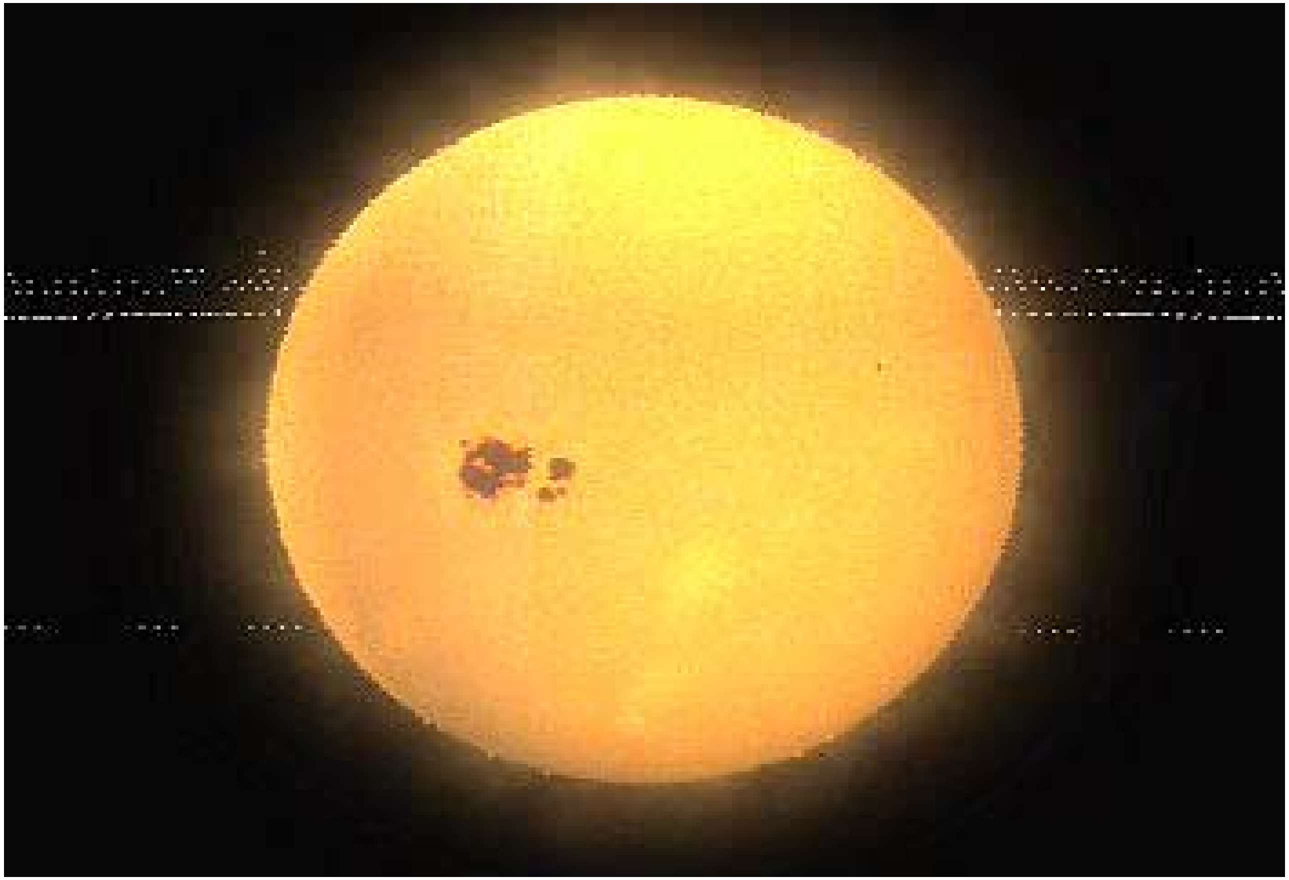


July 10 2000 – February 5, 2001 (7 months); Ulysses poleward of S60 courtesy: J. T. Gosling

Ulysses	LASCO HL	LASCO LL	1 AU
8	101	602	25
8%			4% (8% excluding Backsided CMEs)

~ 10% of CMEs leaving the Sun seem to reach far into the heliosphere Consistent with the 11% wide CMEs; Similar fraction reaches the edge of the LASCO FOV

Animation of Halloween 2003 Events



… to illustrate their heliospheric impact

CMEs and ICMEs:
A tentative correspondence

CMEs Near Sun		ICMEs near Earth
• Shock	→	• Shock
• Frontal	→	• Sheath
• Cavity	→	• Ejecta/MC
• Prominence Core	→	• Pressure Plug
• Arcade Formation		• --------------

Gopalswamy, 2003

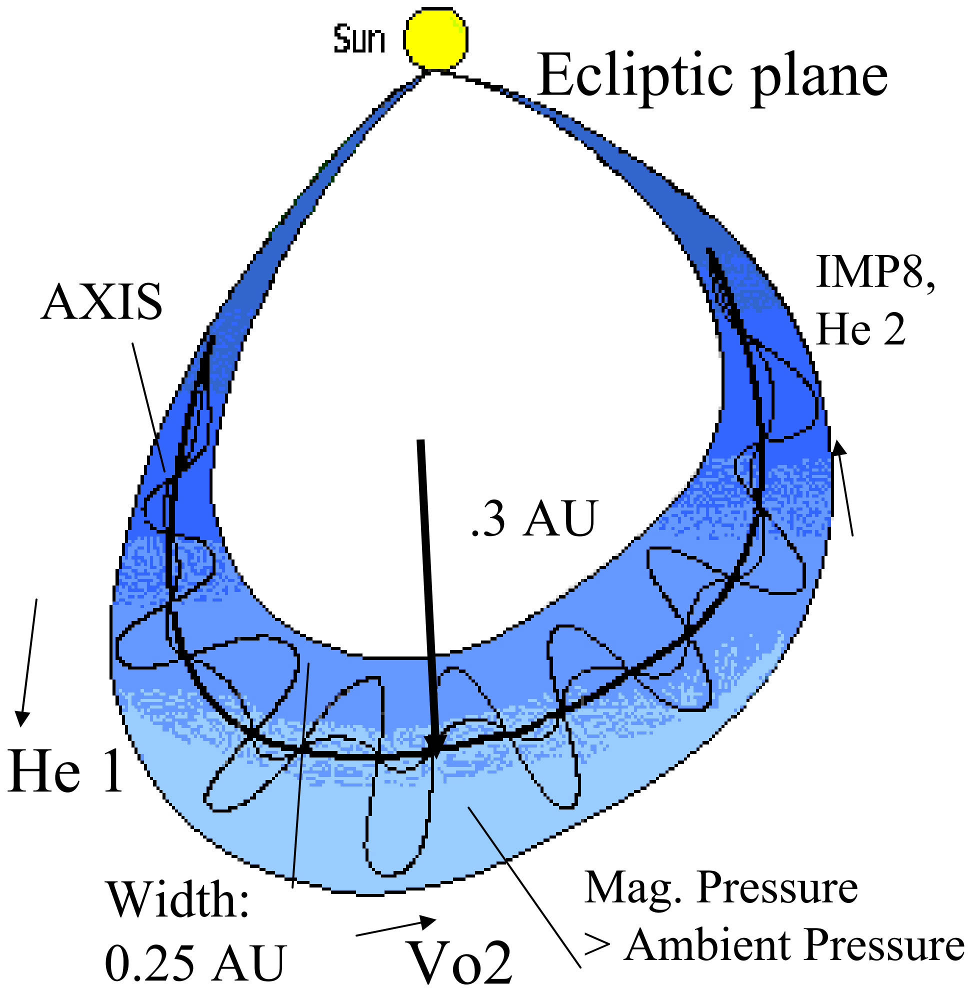
CMEs in the interplanetary medium are known as ICMEs (for Interplanetary CMEs)
CMEs with a flux-rope structure are known as magnetic clouds (MCs)

MCs are ICMEs with enhanced B, smooth rotation, low plasma beta

A Cartoon Model for MCs

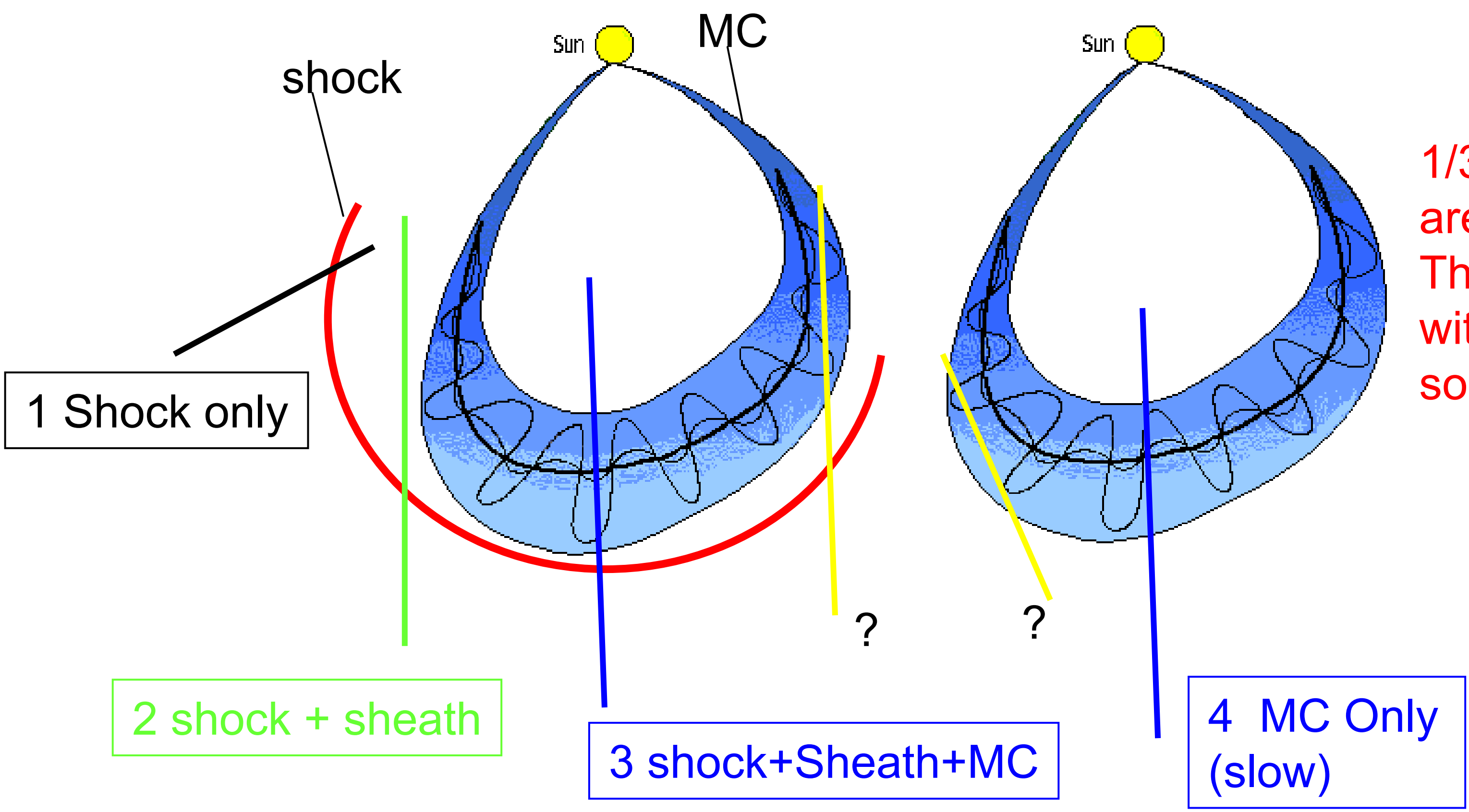
- Burlaga et al. (1990, Geophys. Monograph 58, 373) estimated the curvature of the MC of Jan. 5, 1978 using Helios 1,2, Voyager 2 and IMP8 (Rc = 0.3 AU)
- Extrapolation of the curve suggested connection to the Sun at both ends. MCs are locally cylindrical with a thickness of ~0.25 AU

- Flux Rope Structure from Force Free equilibrium calculations



ICMEs and Magnetic Clouds

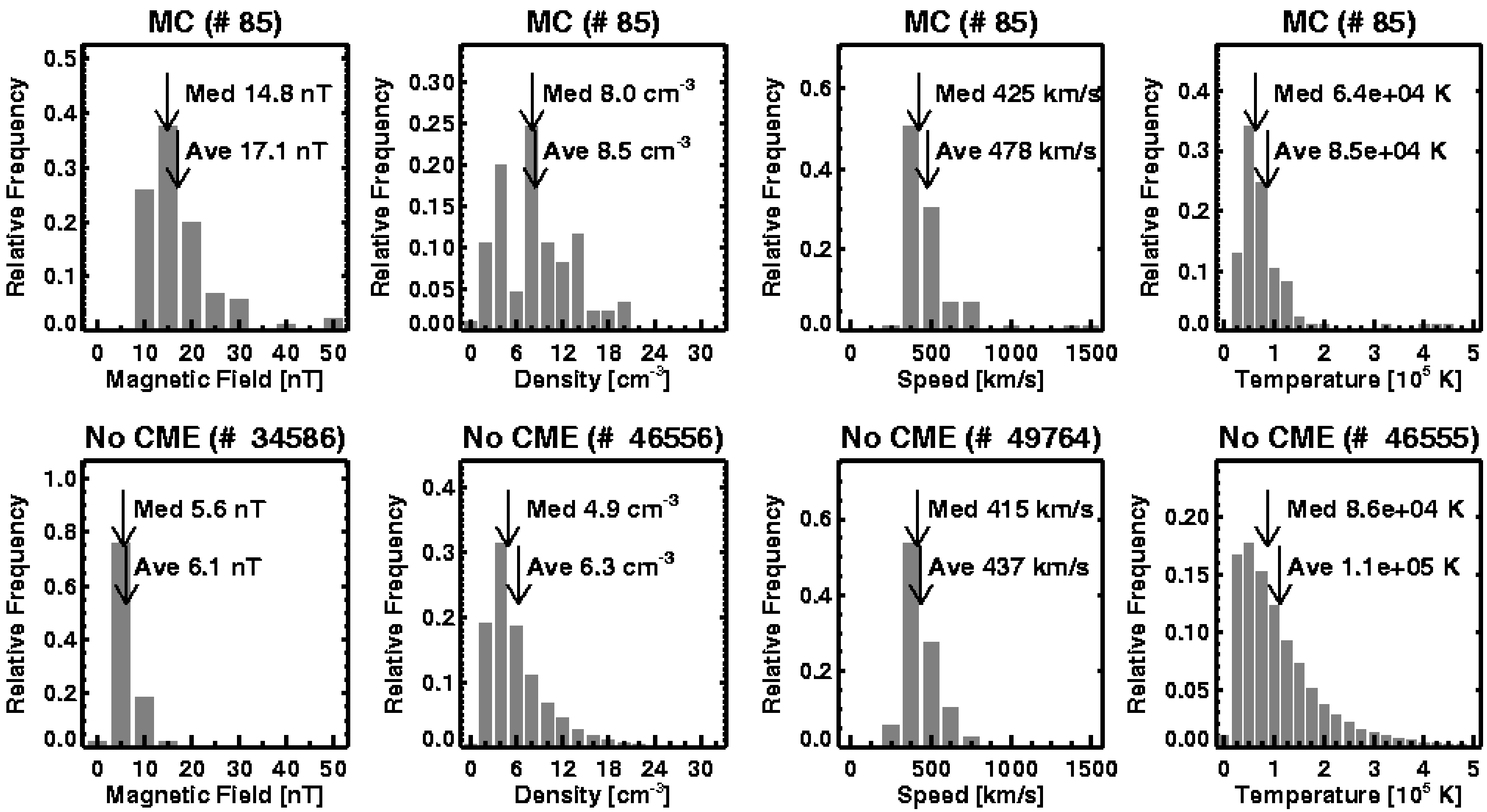
Magnetic Clouds are ICMEs with enhanced B, smooth rotation, low plasma beta



1/3 of all ICMEs are MCs
The ratio changes with phase of the solar cycle

Trajectory of Earth or a spacecraft through ICMEs: All ICMEs may be MCs if the observer is suitably located

MCs and the Solar Wind

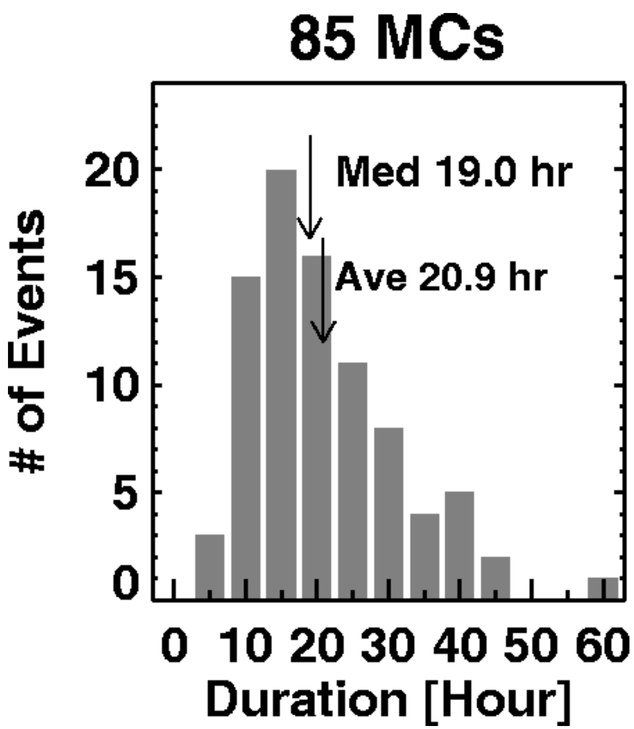


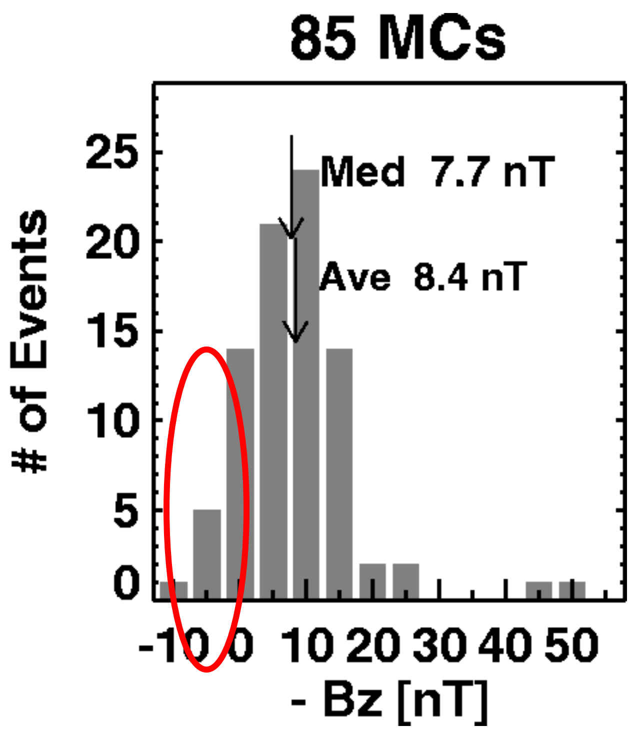
Magnetic Clouds

Solar Wind Excluding CME Intervals

MCs are higher in magnetic field, density, and speed than the solar wind, but slightly cooler than the solar wind

MC Duration and Bz



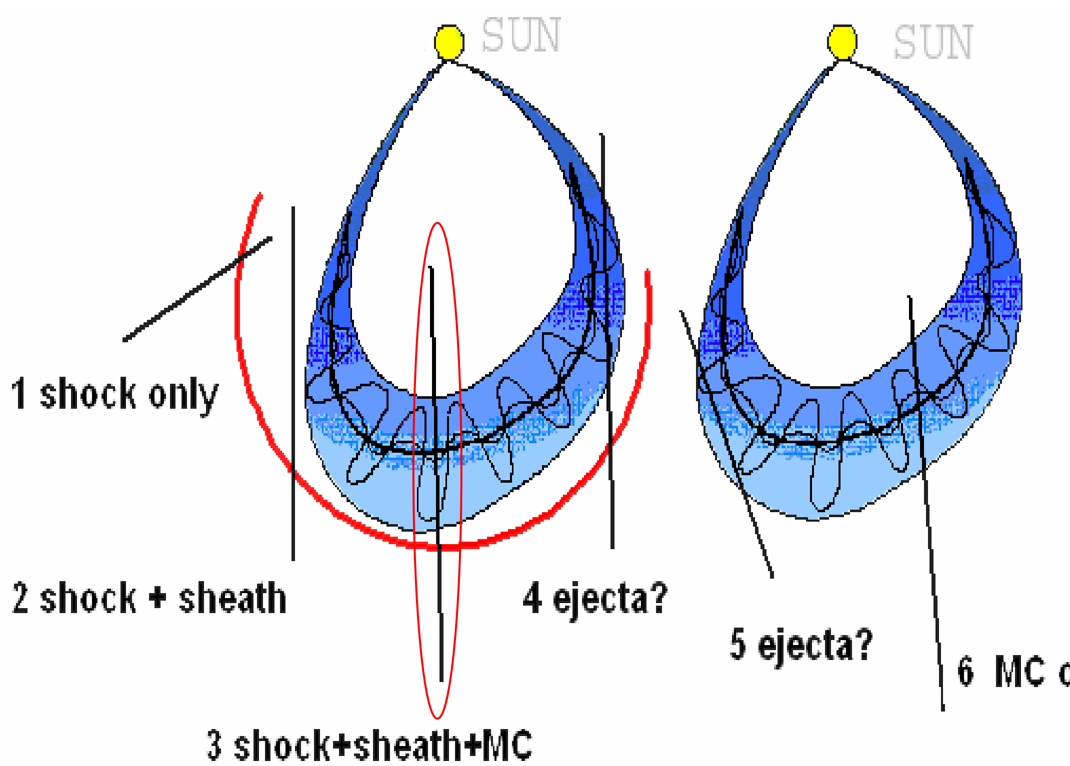


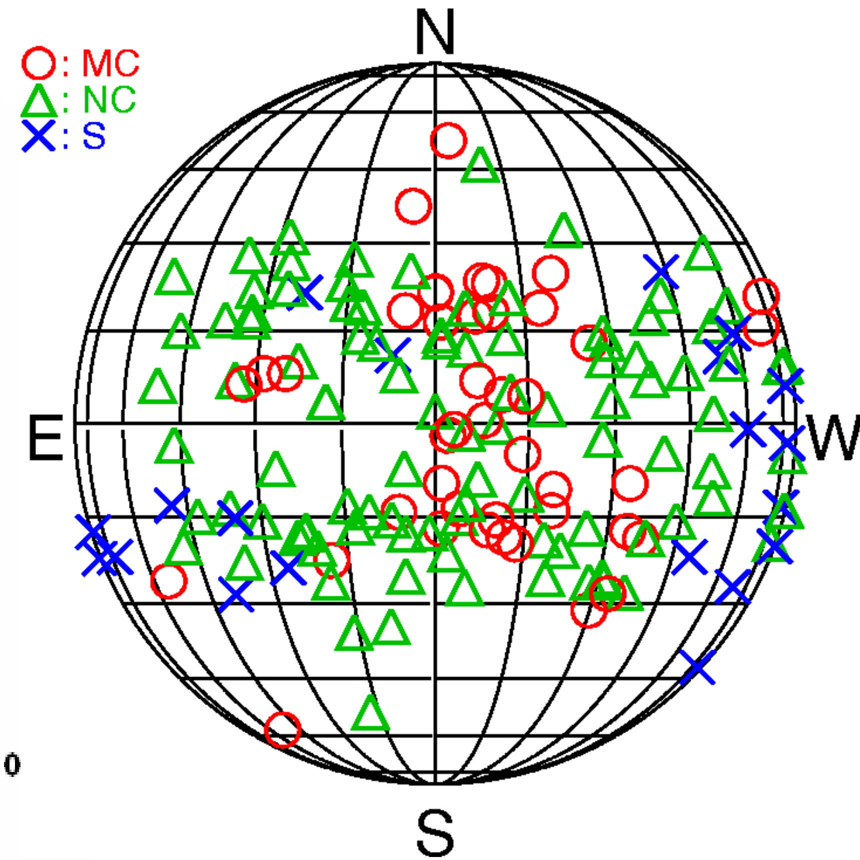
More details on MC properties: Klein and Burlaga, 1982; Gopalswamy et al. 2000; Lepping et al., 2006; Gopalswamy, 2006)

Relative Number of MCs and ICMEs

Magnetic clouds (MCs) generally originate from close to the disk center,
Non-cloud ICMEs (NC) have a large scatter in source locations.
shocks (S) without drivers are due CMEs originating from close to the limb.

Non-cloud: deviation from trajectory 3





MC Topology

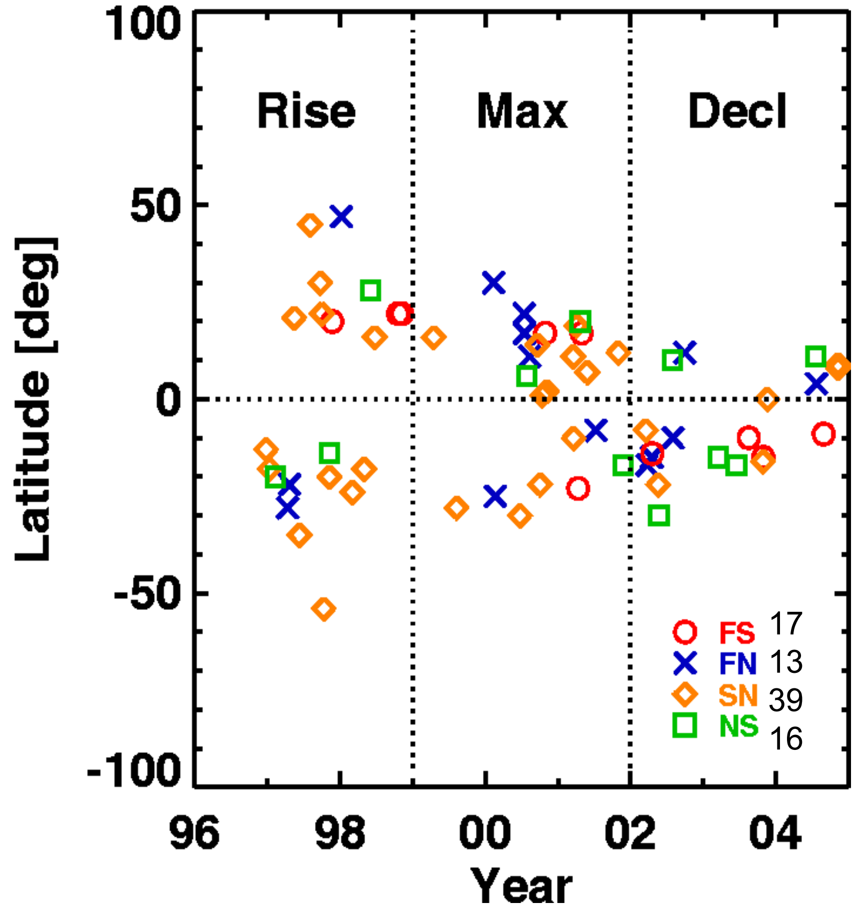
Mulligan et al. 1998

Low inclination

Magnetic Cloud Type	SEN	SWN	NES	NWS
Leading Field	South (-Bz)	South (-Bz)	North (+Bz)	North (+Bz)
Axial Field	East (+By)	West (-By)	East (+By)	West (-By)
Trailing Field	North (+Bz)	North (+Bz)	South (-Bz)	South (-Bz)
Helicity	LH	RH	RH	LH

Magnetic Cloud Type	WNE	ESW	ENW	WSE
Leading Field	West (-By)	East (+By)	East (+By)	West (-By)
Axial Field	North (+Bz)	South (-Bz)	North (+Bz)	South (-Bz)
Trailing Field	East (+By)	West (-By)	West (-By)	East (+By)
Helicity	RH	RH	LH	LH

Gopalswamy, 2006

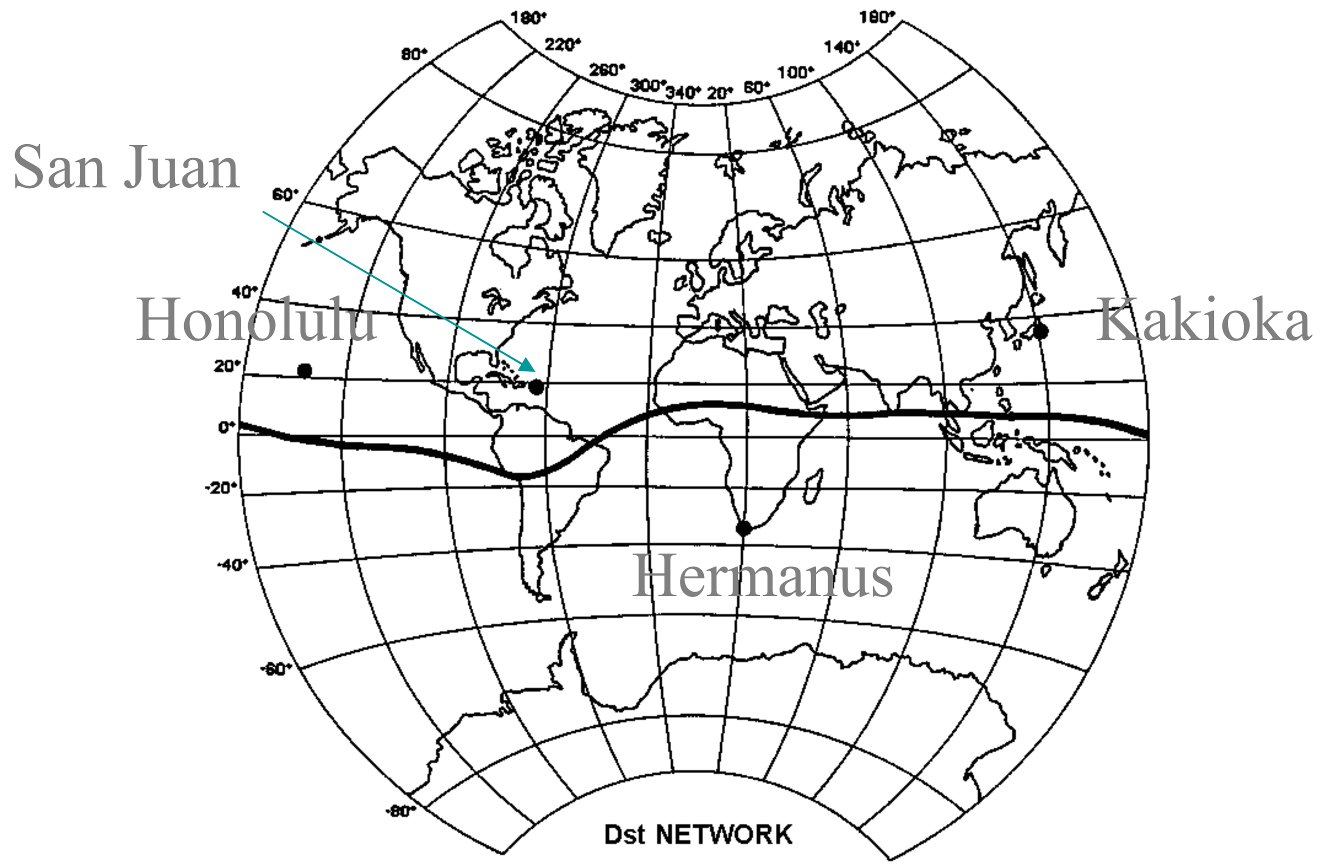


What is a Geomagnetic Storm?

- Earth's magnetic field is disturbed.
- Measurements of horizontal component of Earth's magnetic field show disturbance lasting for a few days
- This is a result of currents induced in Earth's magnetosphere when CMEs impinge on Earth

Dst Network of Observatories

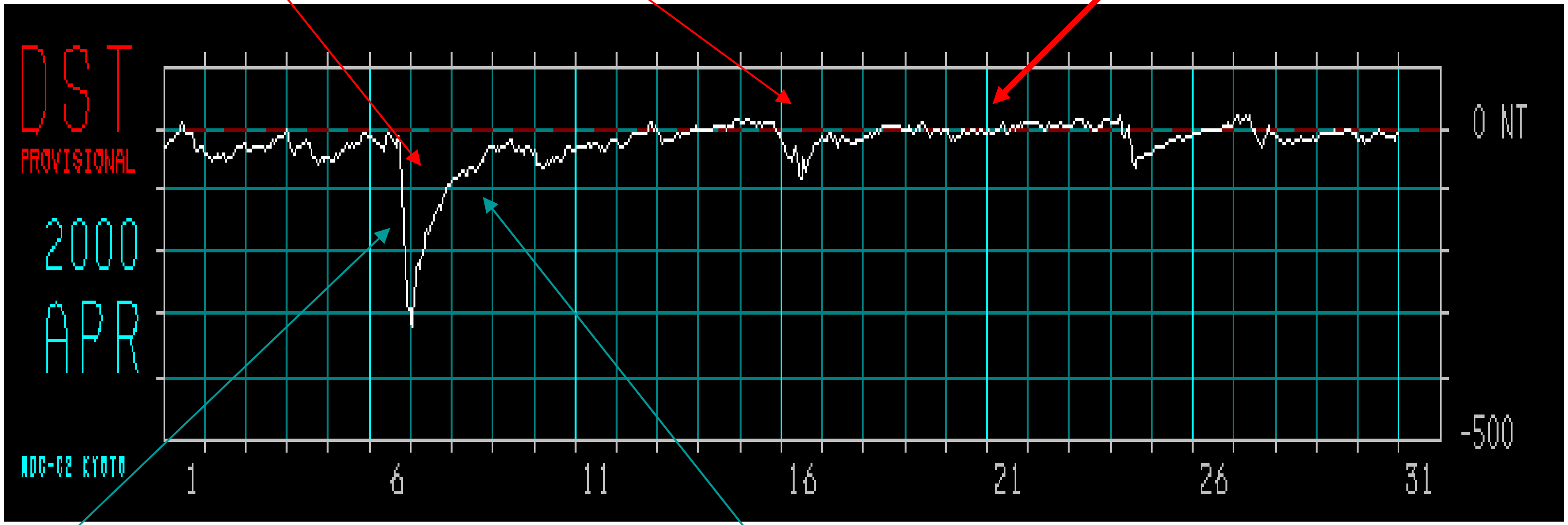
http://swdcdb.kugi.kyoto-u.ac.jp/dst2/onDstindex.html



Example of a Storm

- Dst index for April 2000
- Major and minor storms

Quiet Period



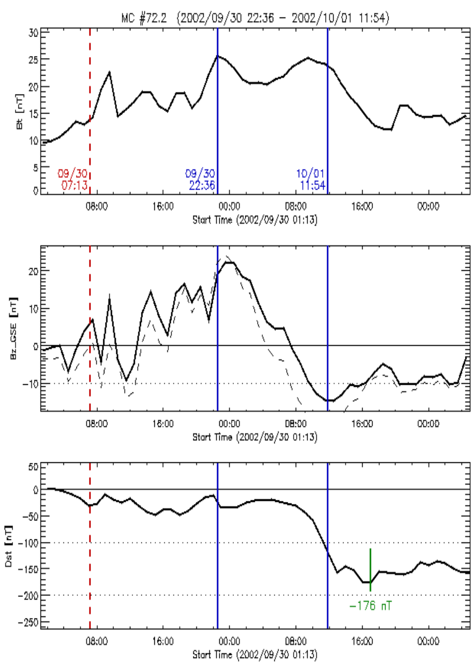
Main Phase

Recovery Phase

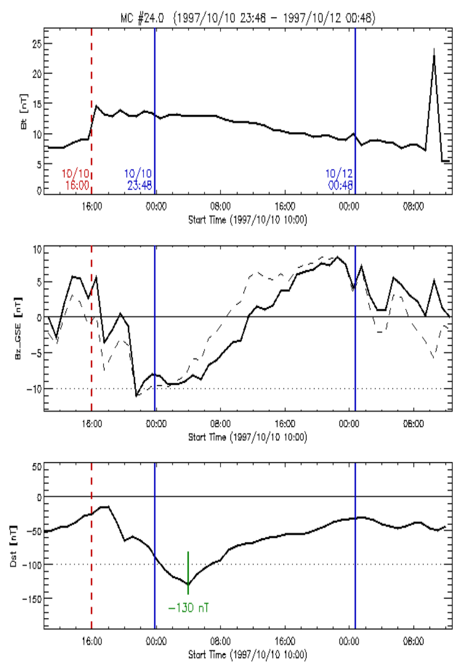
Cloud Types

Each type can have a different sense of rotation of the field

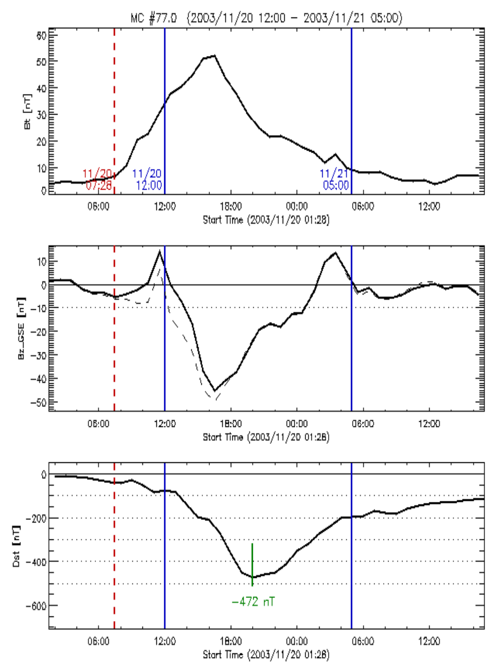
NS (16)



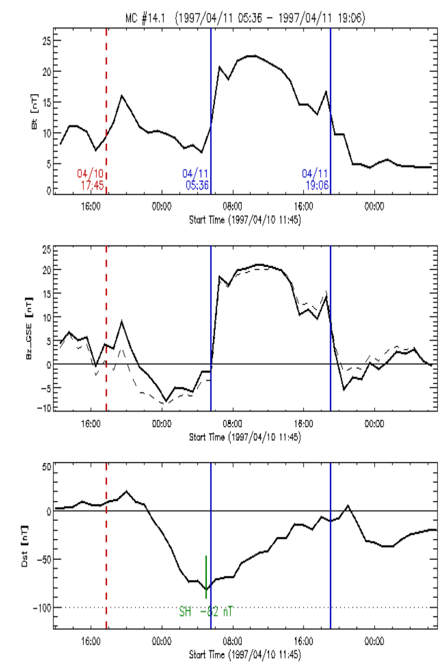
SN (39)



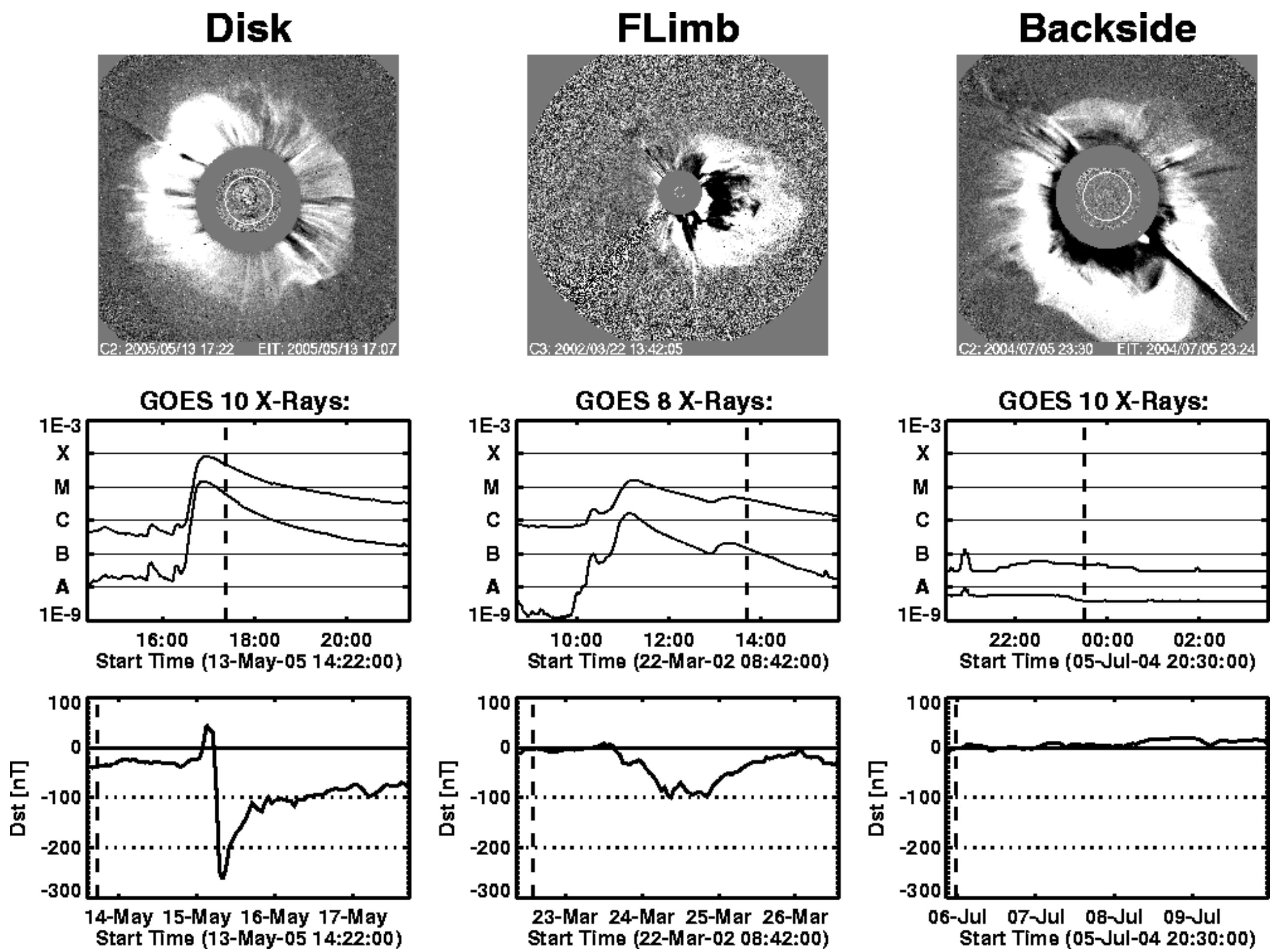
FS (17)



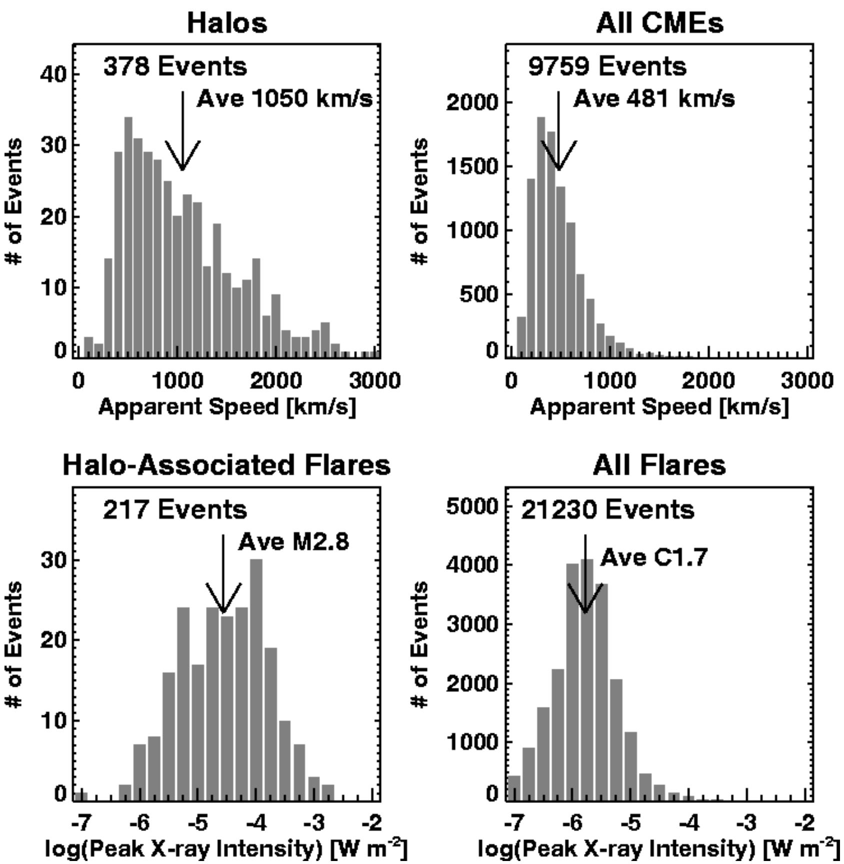
FN (13)



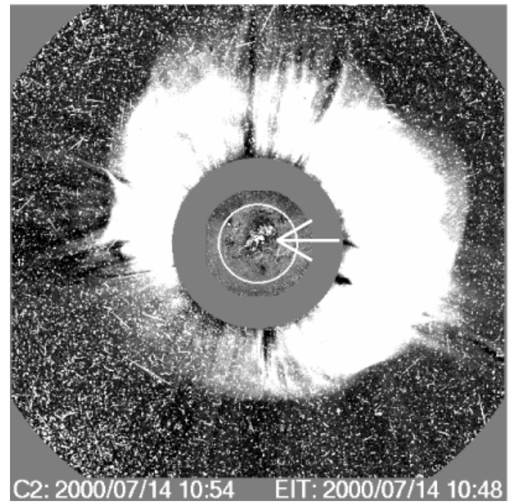
CMEs and Geomagnetic storms



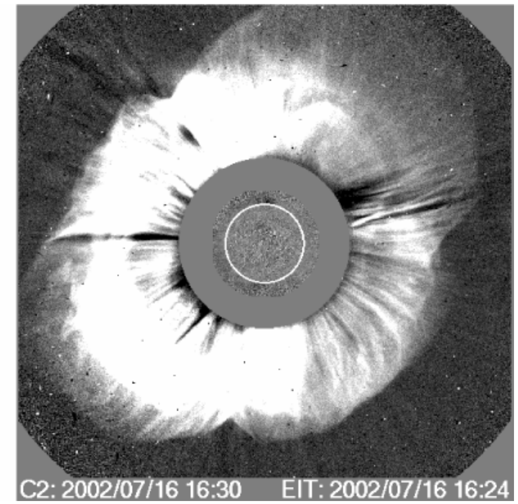
Halo CMEs



Front-side halo



back-side halo

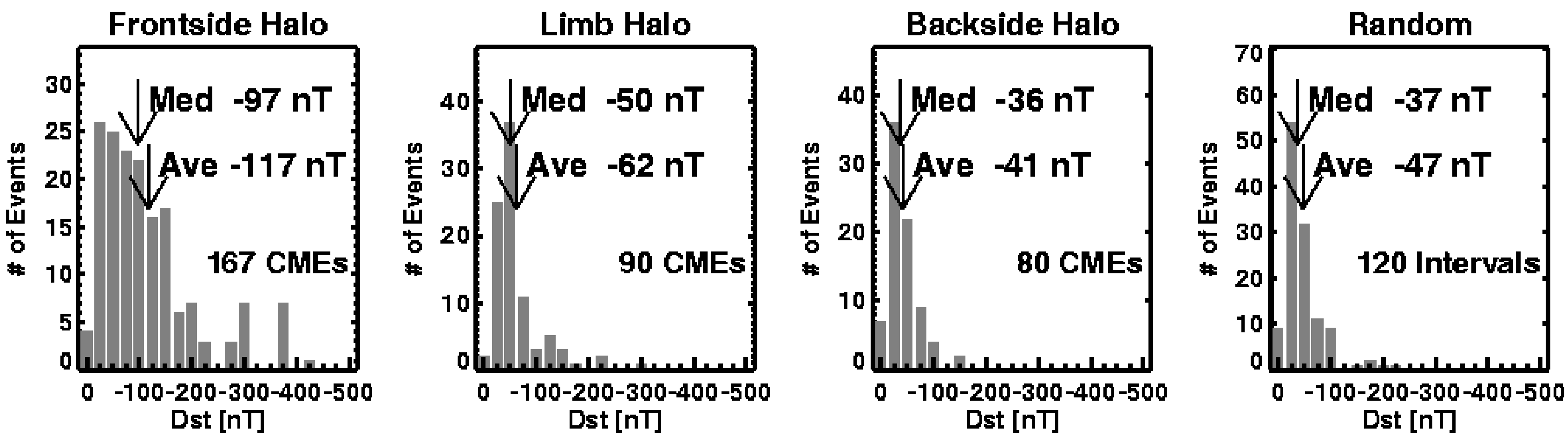


- Halos known for a long time (Howard et al 1982), but routinely observed only by SOHO
- Front-sided halos are likely to impact Earth
- The high kinetic energy of the halos allows them to travel far into the interplanetary medium

- Halos are >2 times faster on the average
- Halos are associated with bigger flares

Geoeffectiveness of Halos

378 halos of cycle 23 analyzed for Geoeffectiveness (Dst < -40 nT)



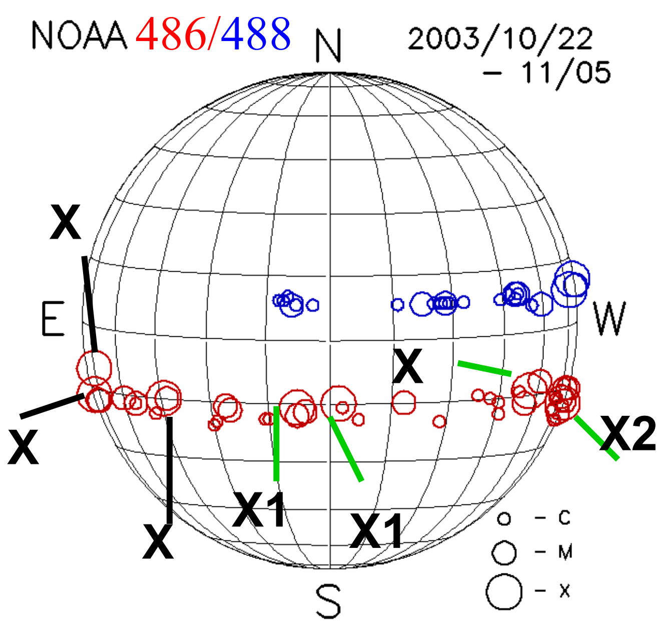
- Source longitude Λ < 45 deg
- Highly geoeffective

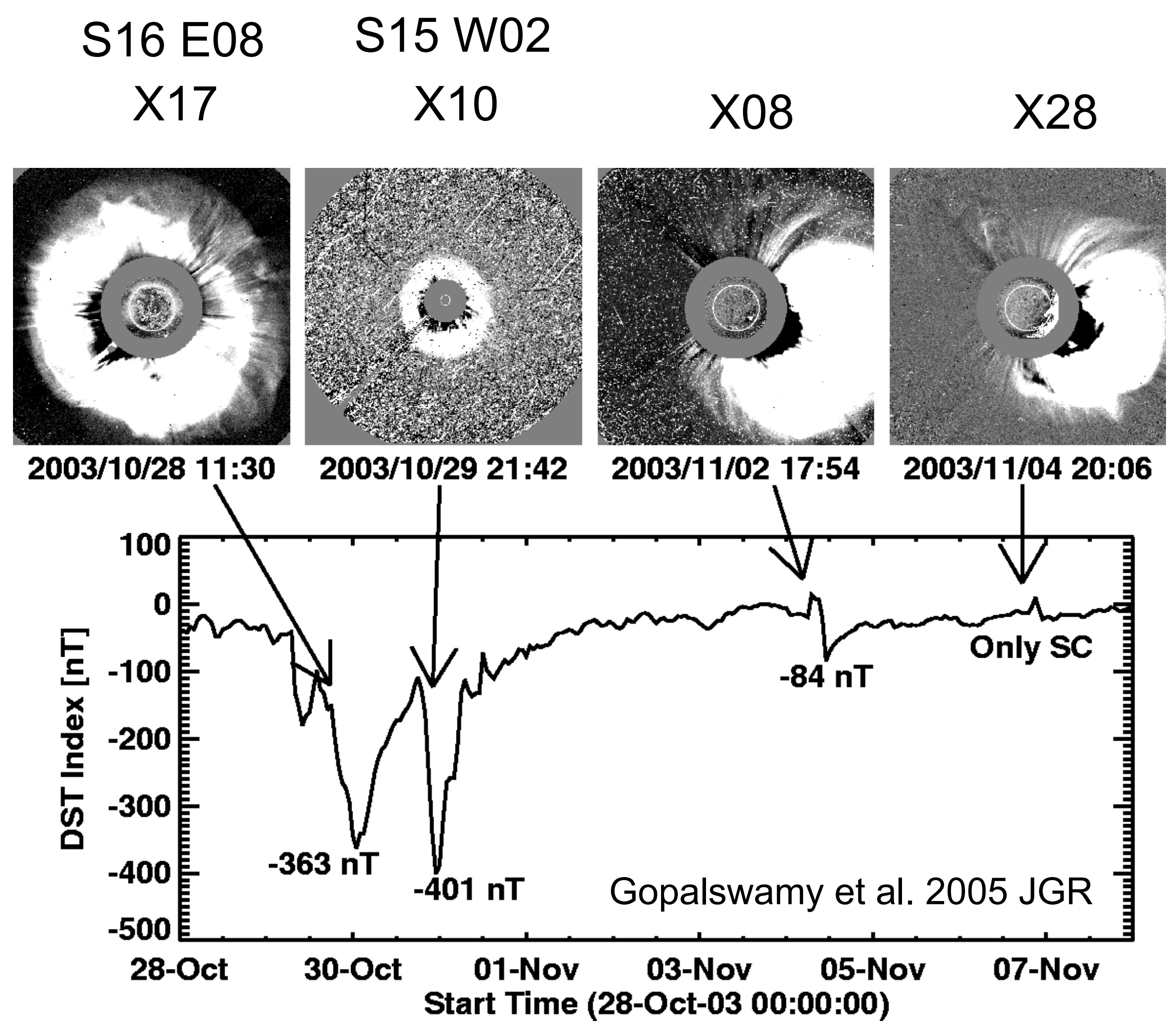
- Source lon 45 < Λ ≤90 deg
- Moderately geoeffective

- Source lon Λ > 90 deg
- Not geoeffective

- Random Dst values
- Similar to Backside halos

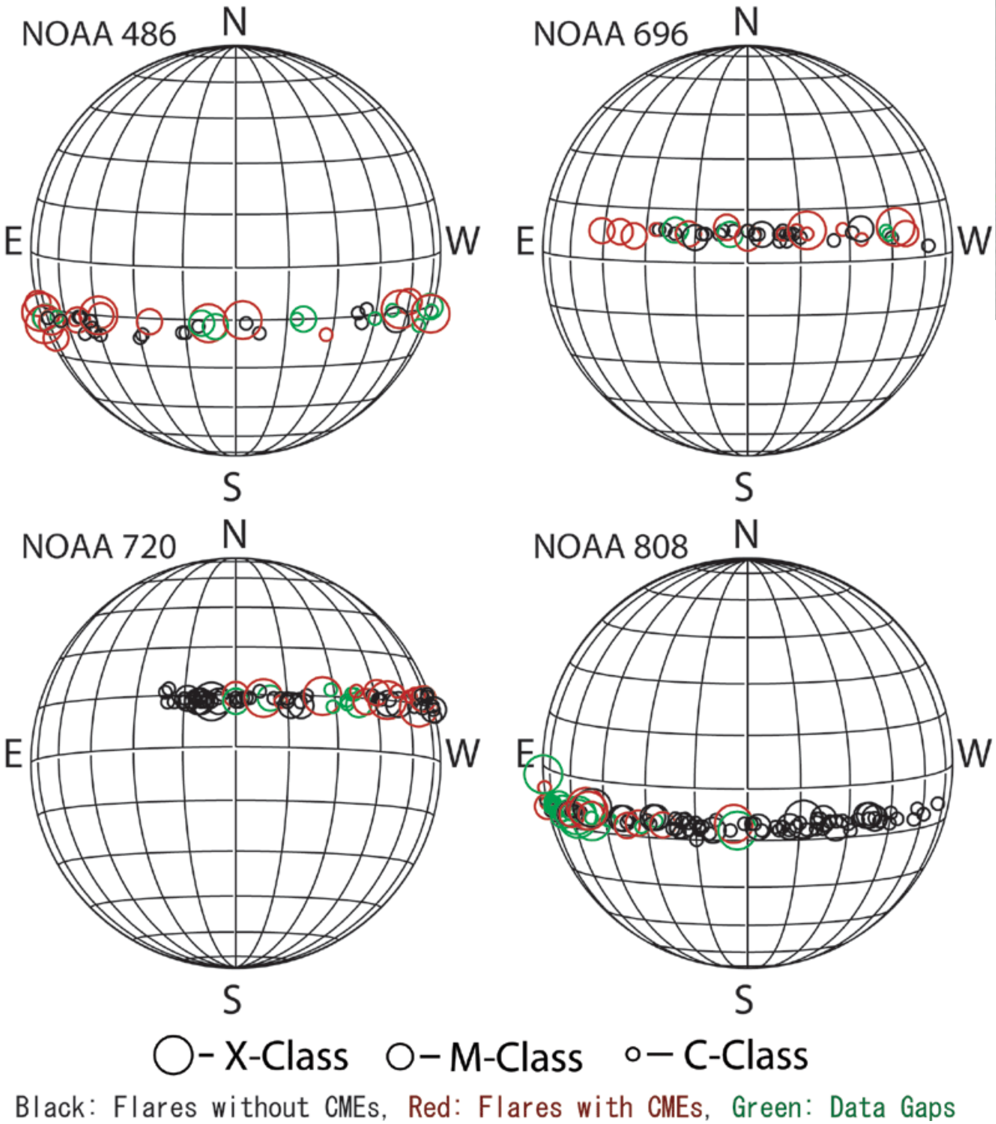
Solar Sources

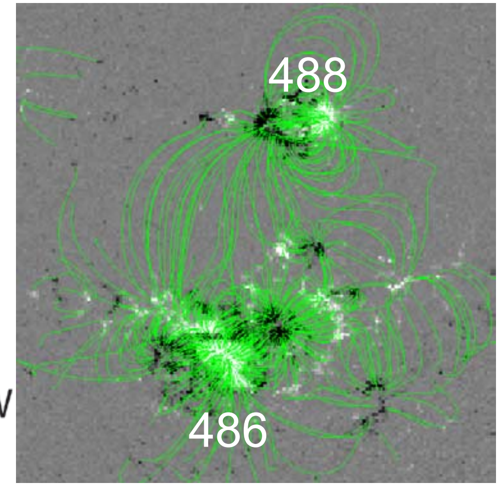




Heliographic coordinates of the associated flare is used as the source location.

Source Locations





MDI magnetogram with extrapolated field lines

AR 486: S15, but transequatorial connection to AR 488 – so highly geoeffective when close to central meridian

AR 696: Lowest latitude. geoeffective When close to central meridian

AR 720: N15 and more westerly. Moderately geoeffective

AR 808: S15, more easterly Moderately geoeffective

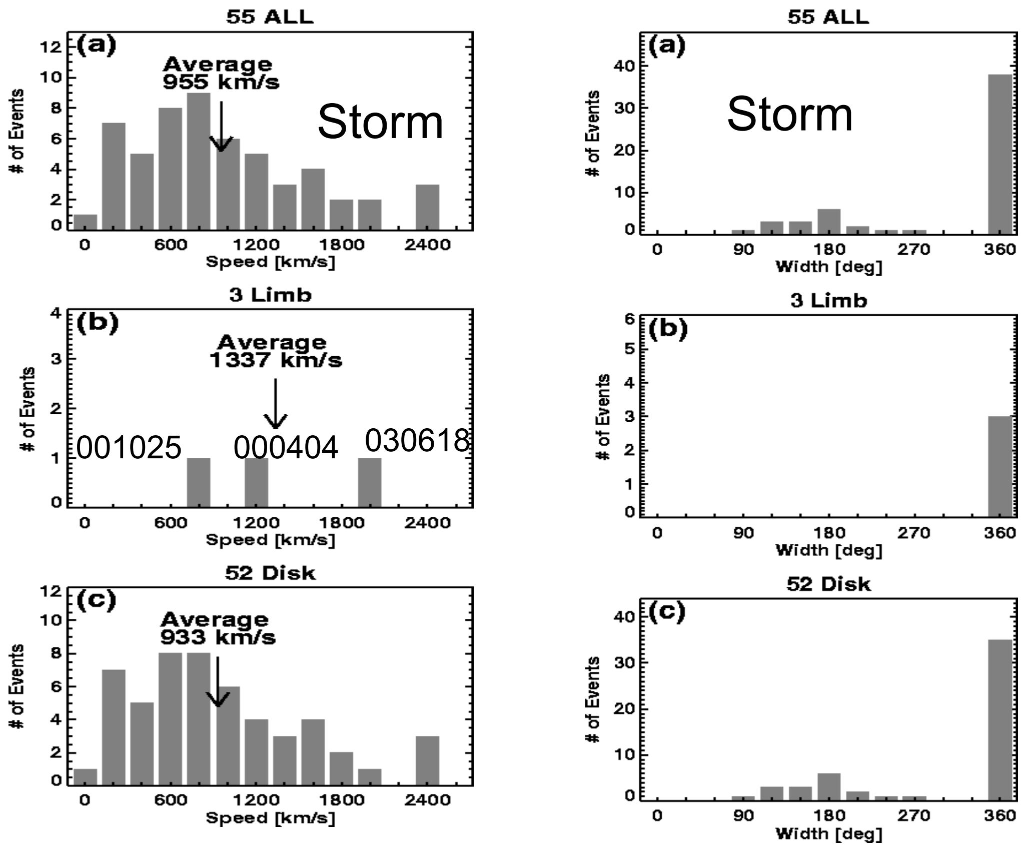
Geoeffective CMEs: Statistics

59 strong (Dst ≤-100 nT) storms (1996-2003) were analyzed (Gopalswamy, 2006)

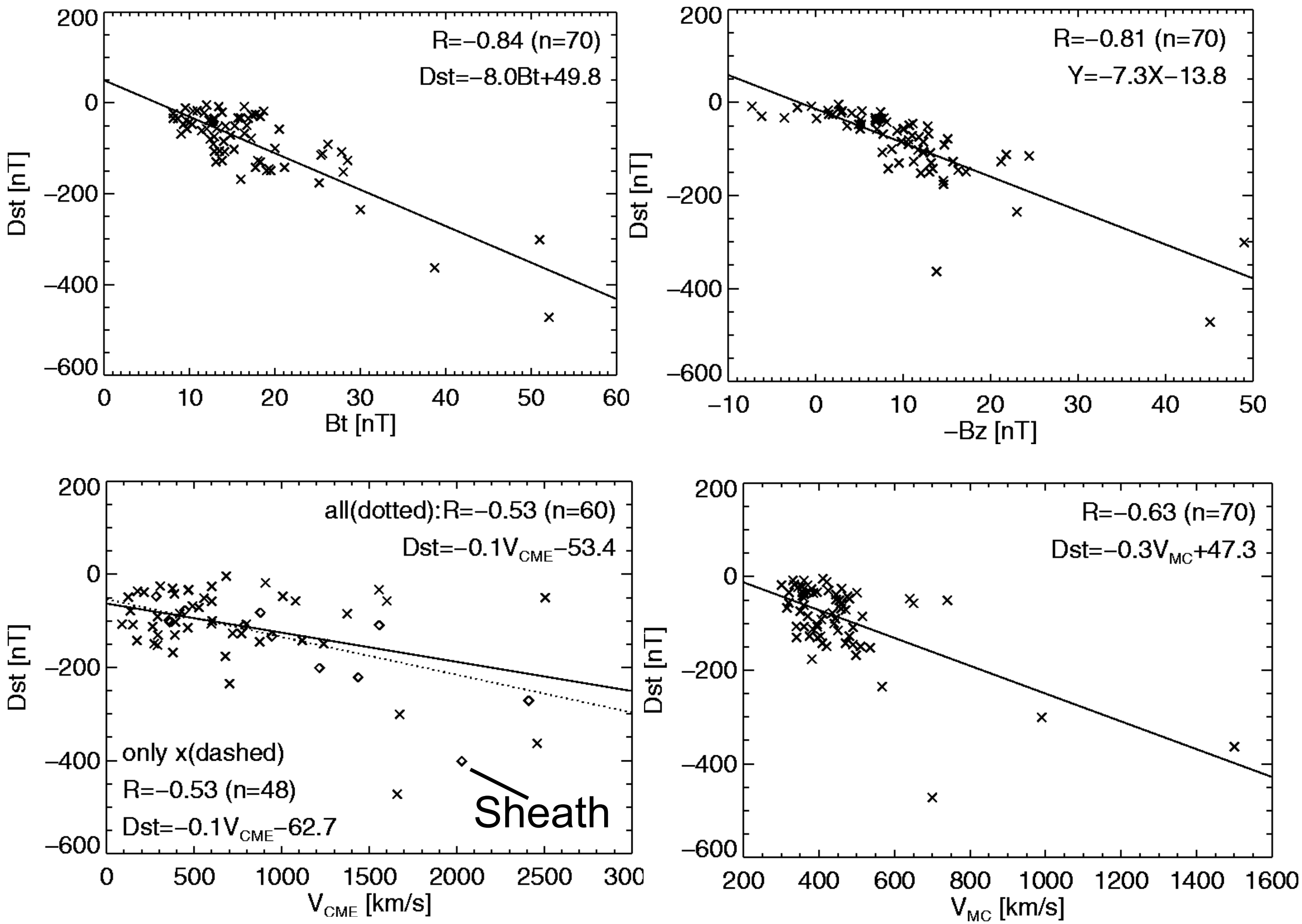
- 55 were CME-associated
- 3 were probably CIR-related
- 1 probably CIR

Geoeffective CMEs are faster and wider on the average.

Mostly full halos (69%) and partial halos (31%)



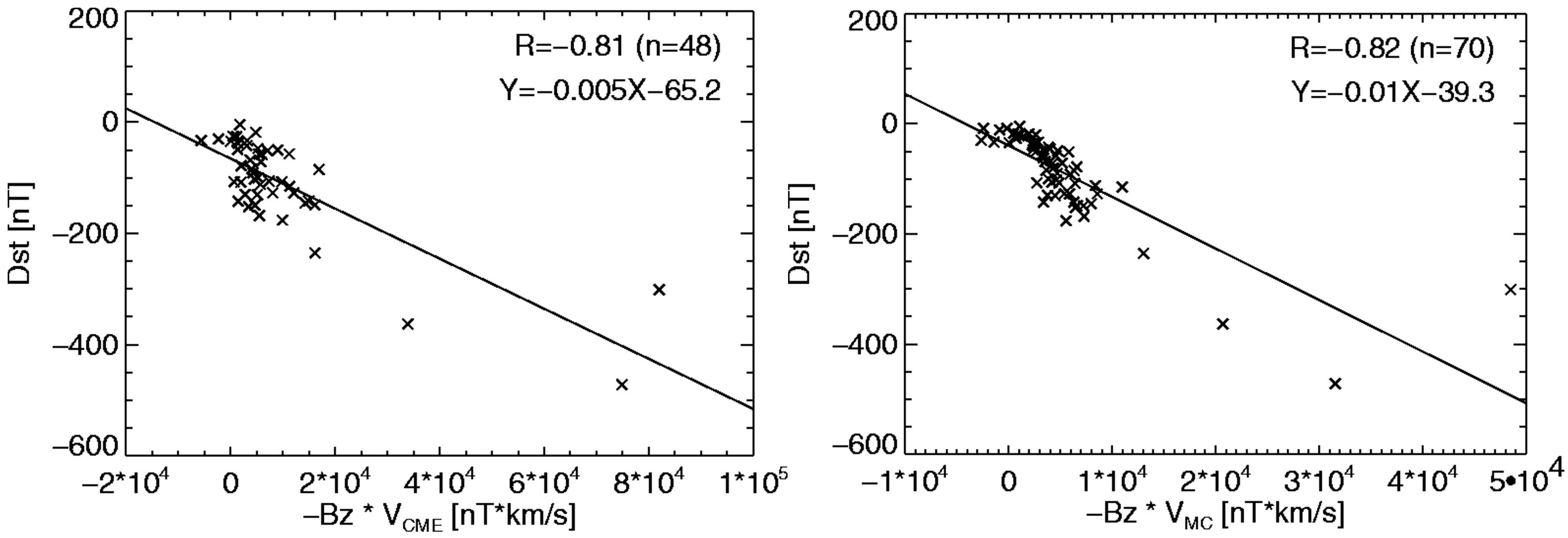
MCs & Geomagnetic Storms: Statistics



The correlation of Dst is the lowest with CME speed

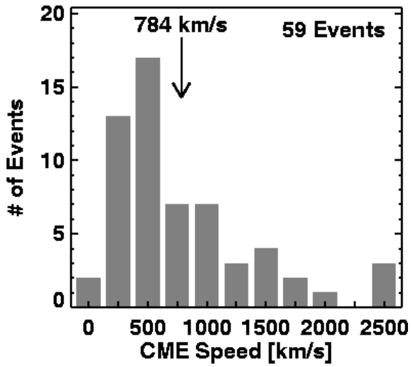
and highest with the strength of the MC magnetic field

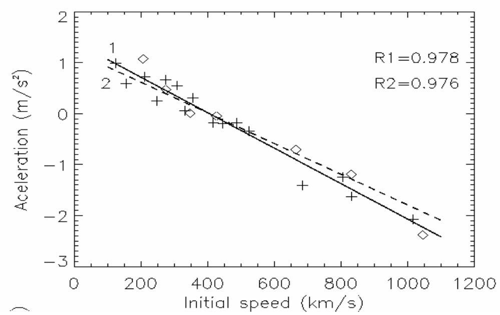
MCs & Geomagnetic Storms: Statistics

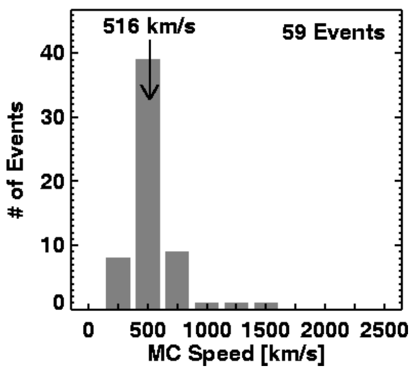


Good correlation between Dst and the product of CME speed and Bz
Very useful if we can estimate Bz or B in CMEs near the Sun!

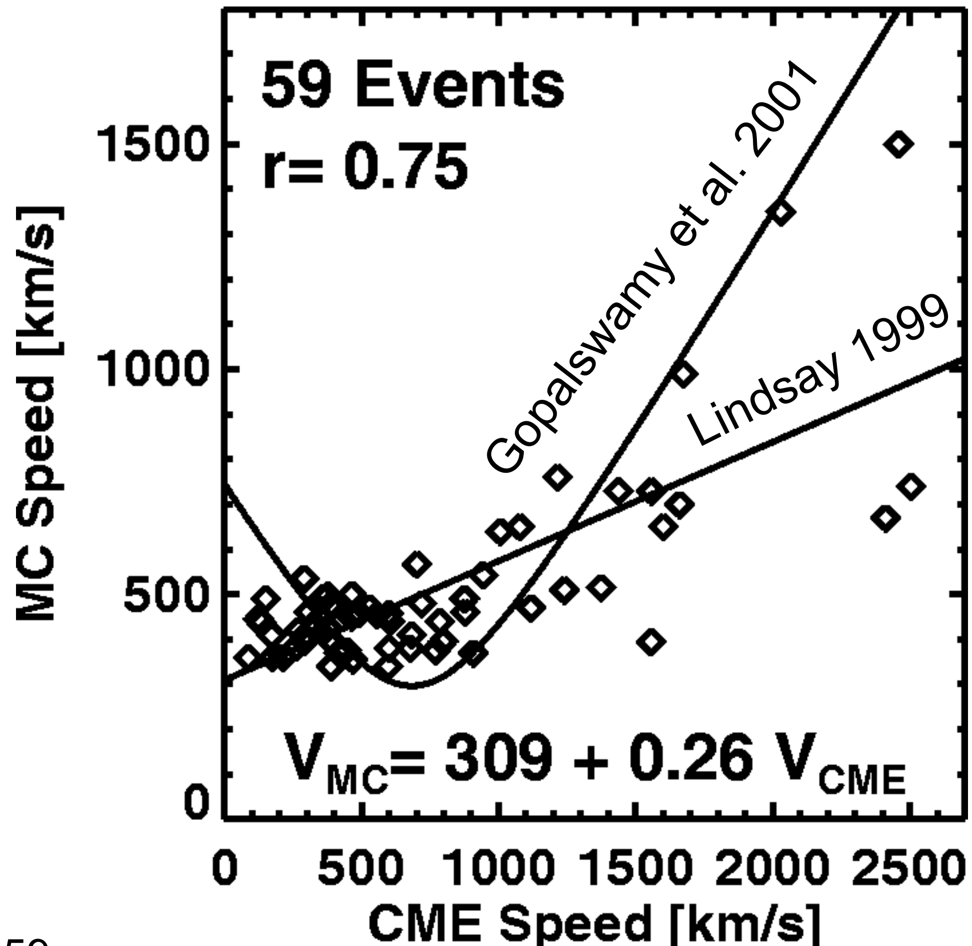
CME-ICME Relationship







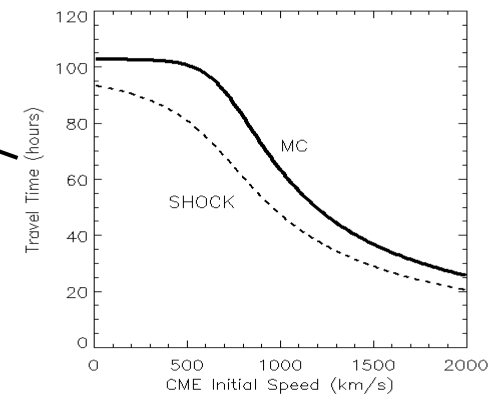
a = - 0.0054V + 2.193
a = - 0.0054 (V – 406)
a =0 for V=406 → CMEs riding on the solar wind



The speed distribution of CMEs and ICMEs for 59 pairs (from Gopalswamy et al. 2000 GRL).

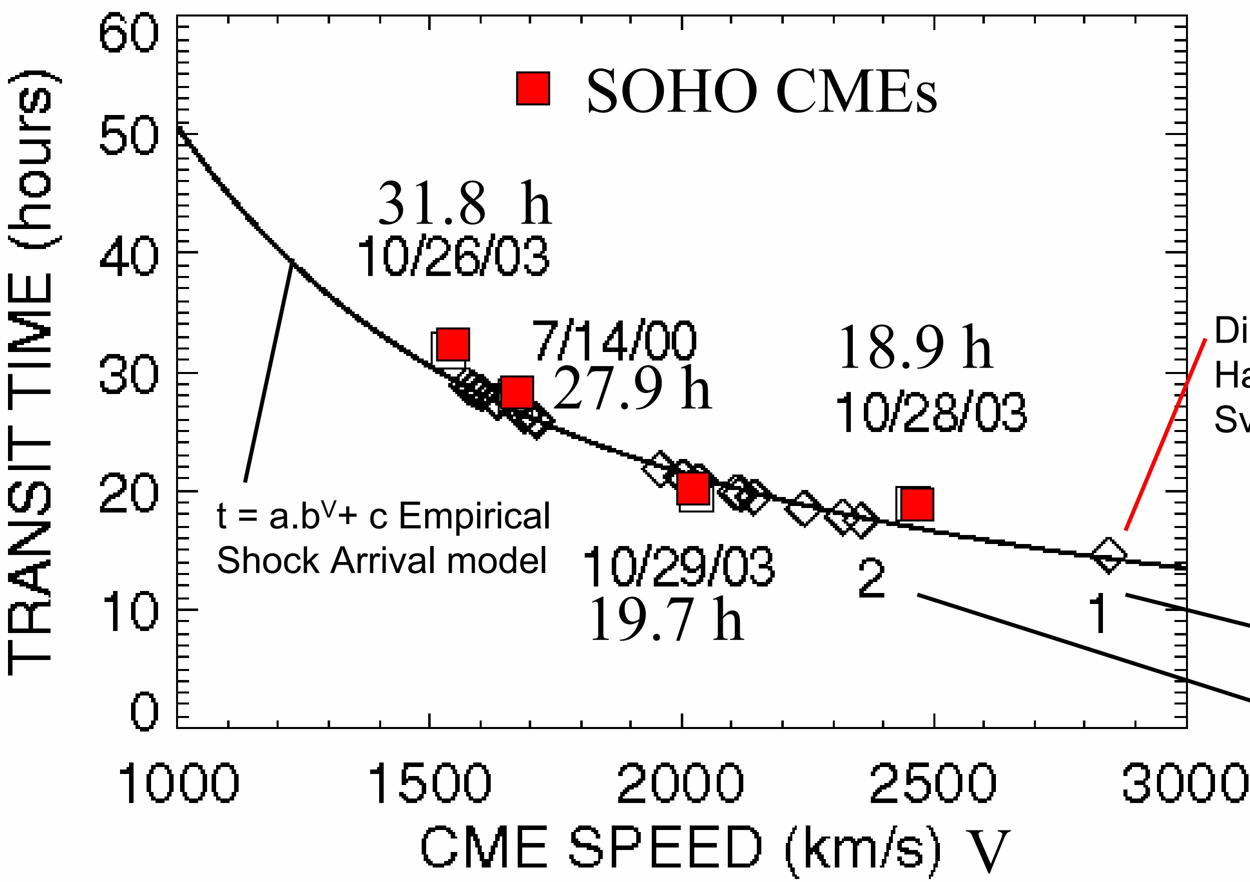
Transit Time of Shocks & CMEs

The IP acceleration can be used to estimate the CME transit time to Earth. The shock transit time can be obtained from the CME transit time by estimating the standoff distance.



Empirical models for shock and CME arrival at Earth

SOHO contributed 2 events to the historical fast transit events compared with a simplified formula for the shock transit time.



Diamonds: historical flare-SSC time from Hale 1931, Newton, 1943, Cliver & Svalgaard 2004, Gopalswamy et al 2005

Aug 4, 1972

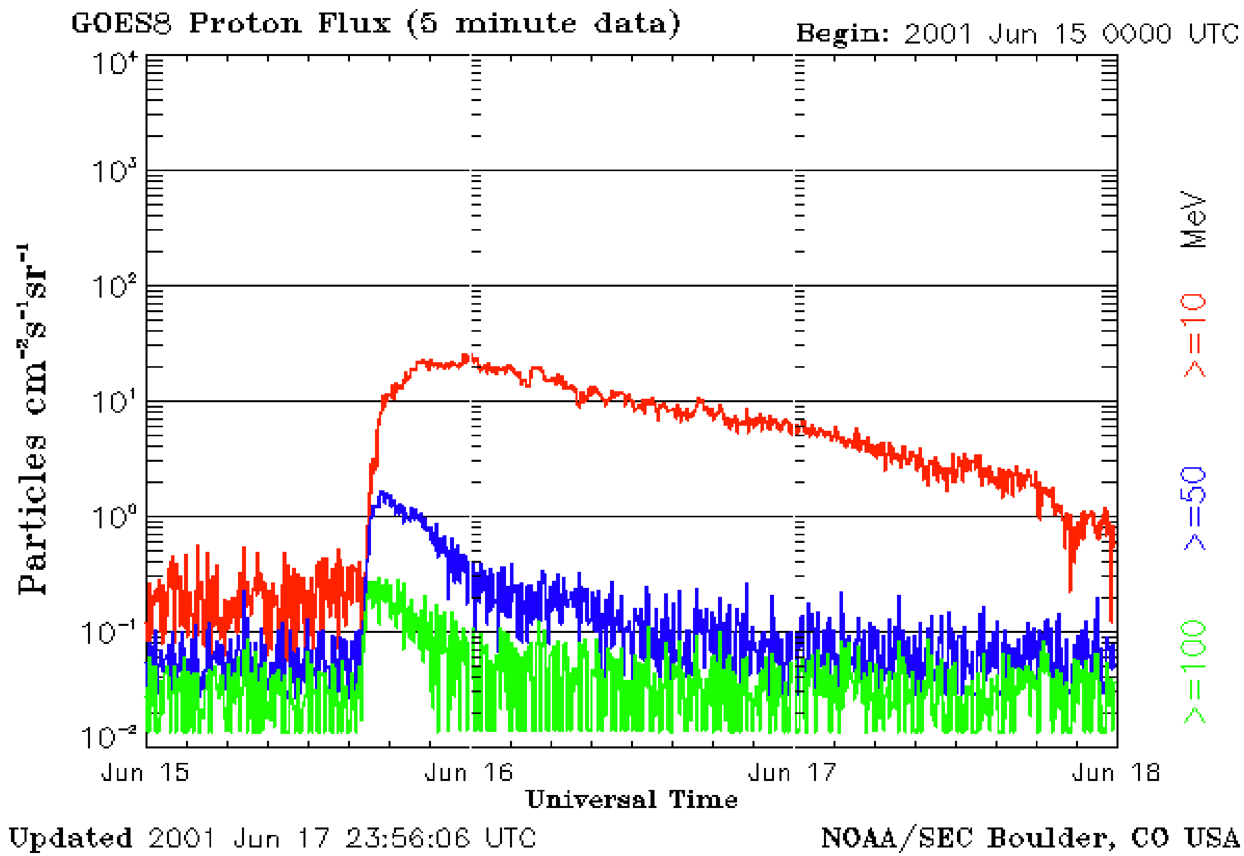
Sep 1, 1859 Carrington

From Gopalswamy et al. 2005 JGR

Proton Shower from the Sun

Solar energetic particles (SEPs) are measured in units of
Particle flux units (pfu): 1 pfu = 1 particle/cm^2/s/sr
Discovered by Forbush (1946)

SEPs can damage Space Electronics, Solar Cells, and pose radiation hazard to astronauts who space walk.



2006 Dec 12 IIA KKL

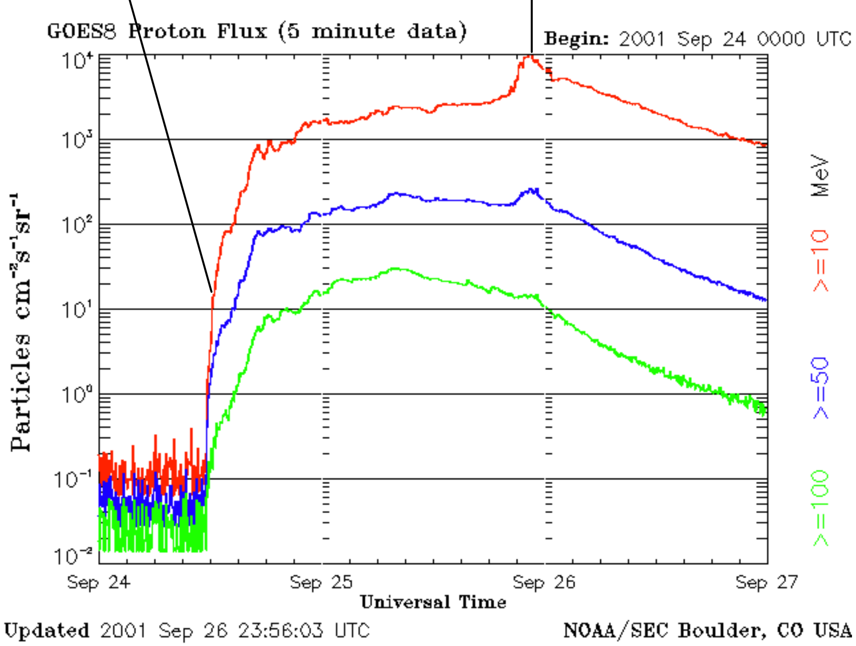
Radiation hazard is of primary concern for space missions

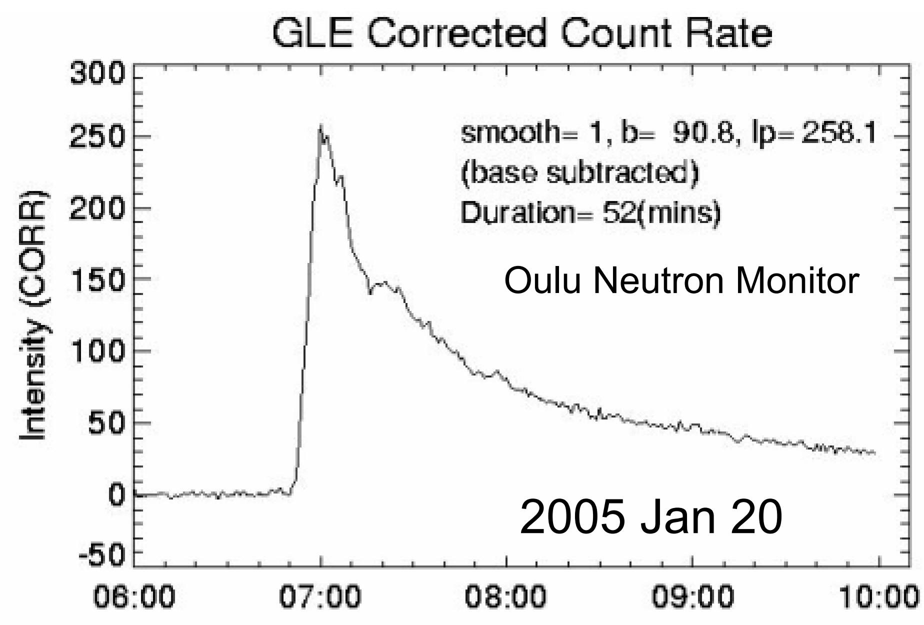
CME-related Energetic Particles

SEPs accelerated when the shock is far away from the detector

Energetic Storm Particle (ESP) events: acceleration when the shock is at the detector

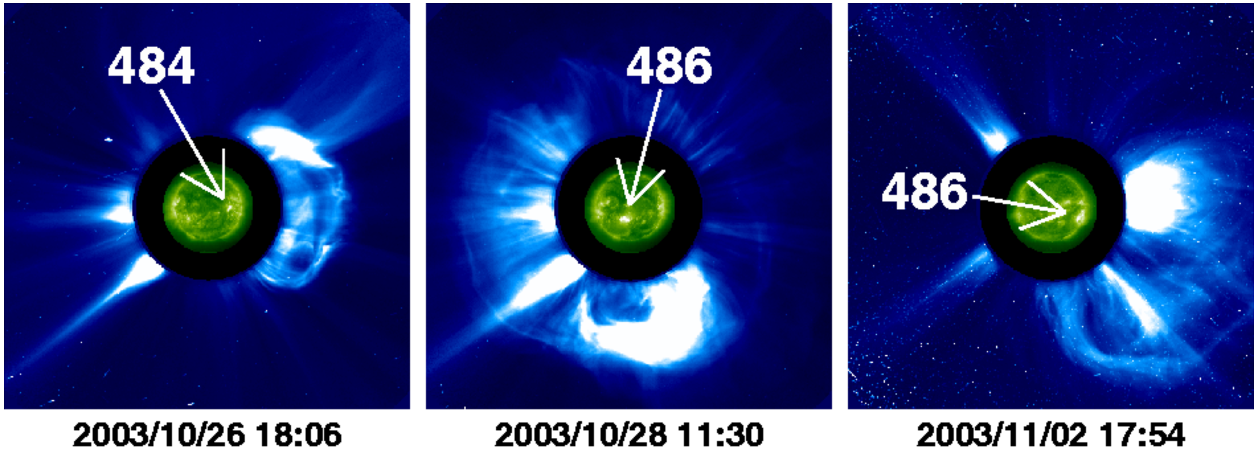
SEPs with ground-level enhancements





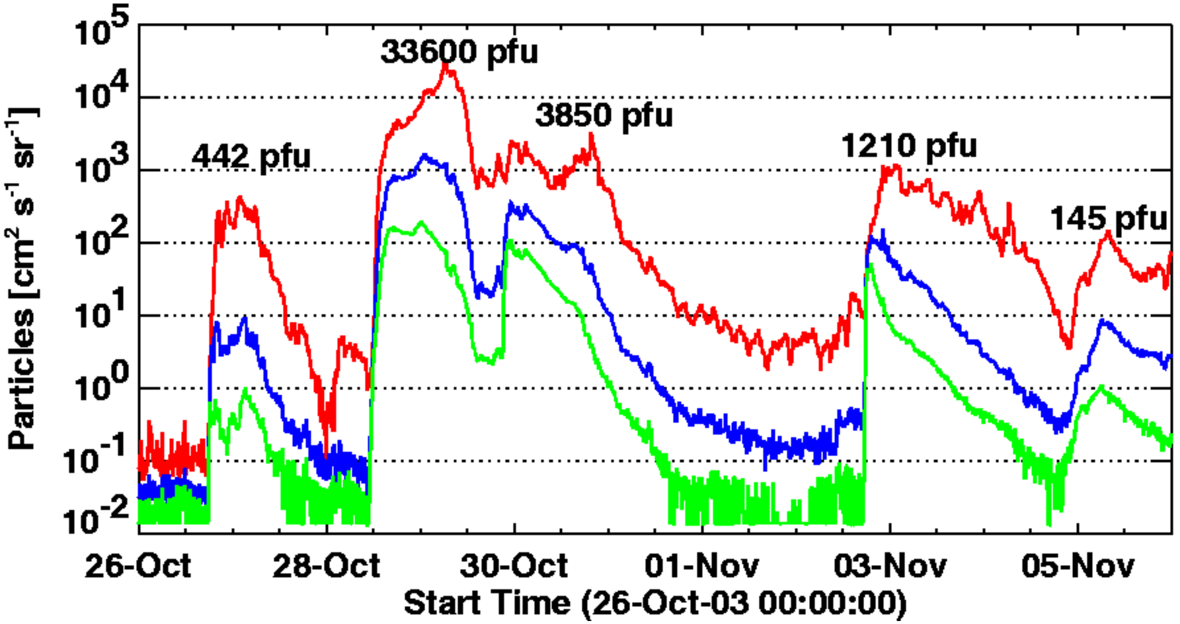
CMEs and SEPs

At least 5 large SEP Events
- Mostly from 486
- One from 0484
-10/28 CME produced the largest > 10 MeV flux (33,600 pfu)



>10^4 pfu Events: Cycle 23

10/28/03	33,600
11/04/01	31,700
07/14/00	24,000
11/22/01	18,900
11/08/00	14,800
09/24/01	12,900



Bigger (since 1976):

10/19/1989 – 40,000
03/21/1991 – 43,000

N. Gopalswamy

Type II Bursts & SEPs

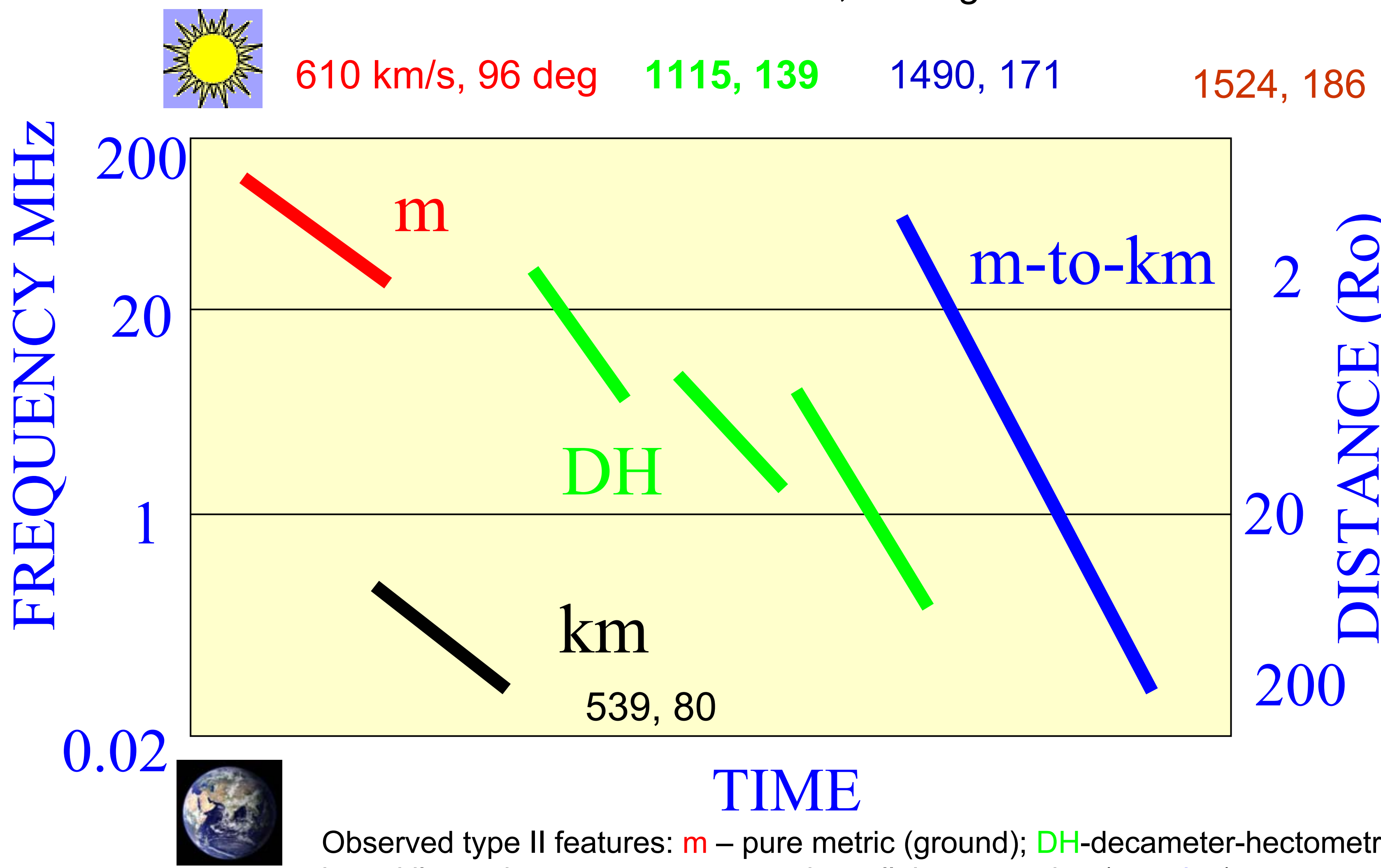
- Close similarity between mkm type II bursts and SEP events: both due to CME-driven shocks

- Type II bursts arrive at Earth in about 8 minutes, and hence provide advanced warning of shocks leaving the Sun. A 1500 km/s shock would have traveled only a distance of about 1 Rs over the time taken by type II bursts to reach Earth.

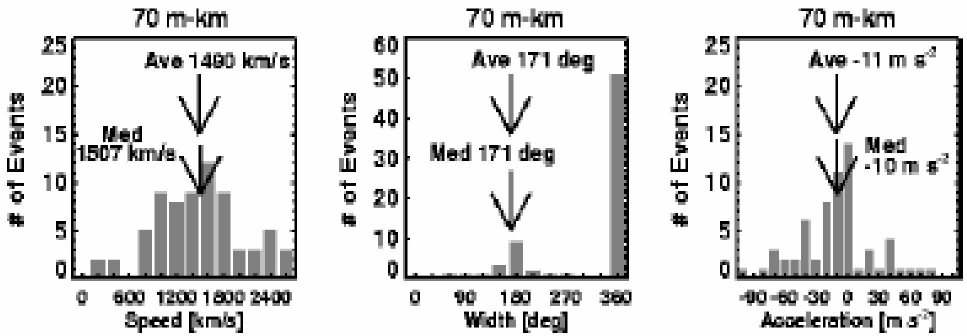
- Type II bursts occurring over a wide range of wavelengths identify shocks that propagate far into the IP medium.

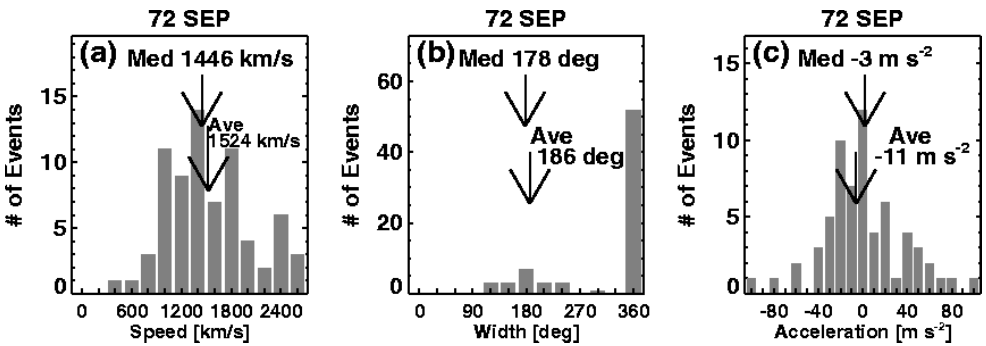
Shock Signature: Type II Bursts

All CMEs: 452 km/s, 45 deg



Observed type II features: m – pure metric (ground); DH-decameter-hectometric; km – kilometric; some start at m and go all the way to km (m-to-km)

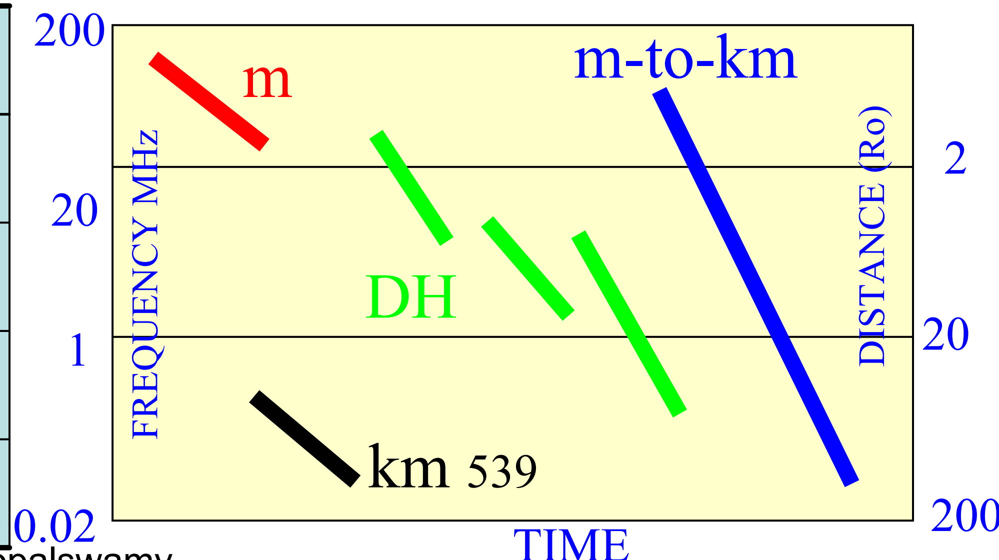




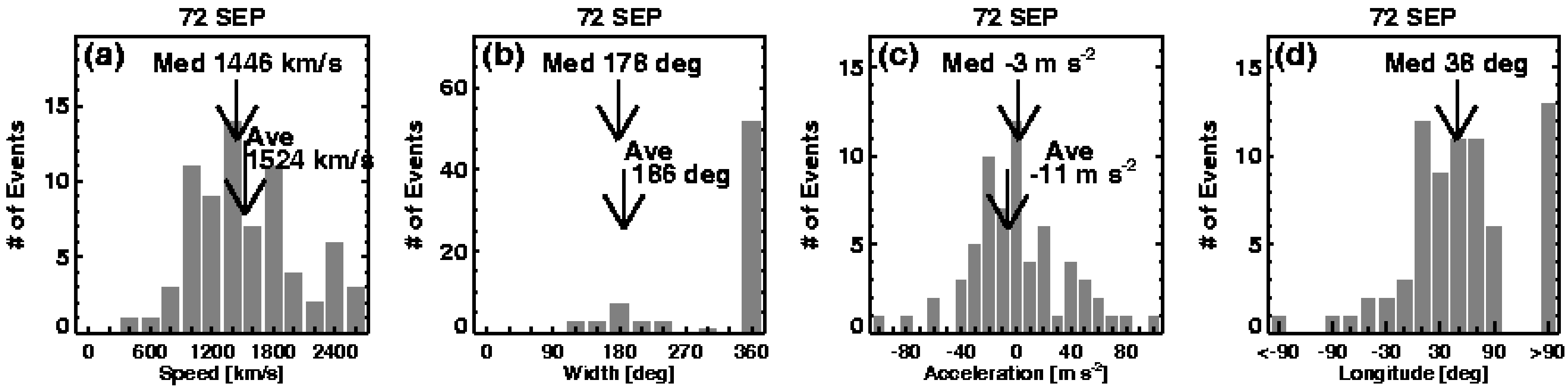
CME-Type II Hierarchy

- The CME kinetic energy (speed, width) decides the wavelength range of type II bursts.
- Speed, width, & deceleration progressively increase for CMEs associated with metric, Decameter-hectometric (dh) and metric to kilometric (m-to-km) Type II bursts
- km type IIs have positive acceleration → shock formation at large distances from the Sun
- CMEs with m-to-km type II bursts are also associated with SEP events (same shock accelerates electrons & protons)

CME Property	All	m	DH	mkm SEP	km
Speed (km/s)	487	610	1115	1490 1524	539
Width (deg)	45	96	139	171 186	80
Halos (%)	3.3	3.8	45.2	71.4 72	17.2
Accel. (m/s²)	-2	-3	-7	-11 -11	+3



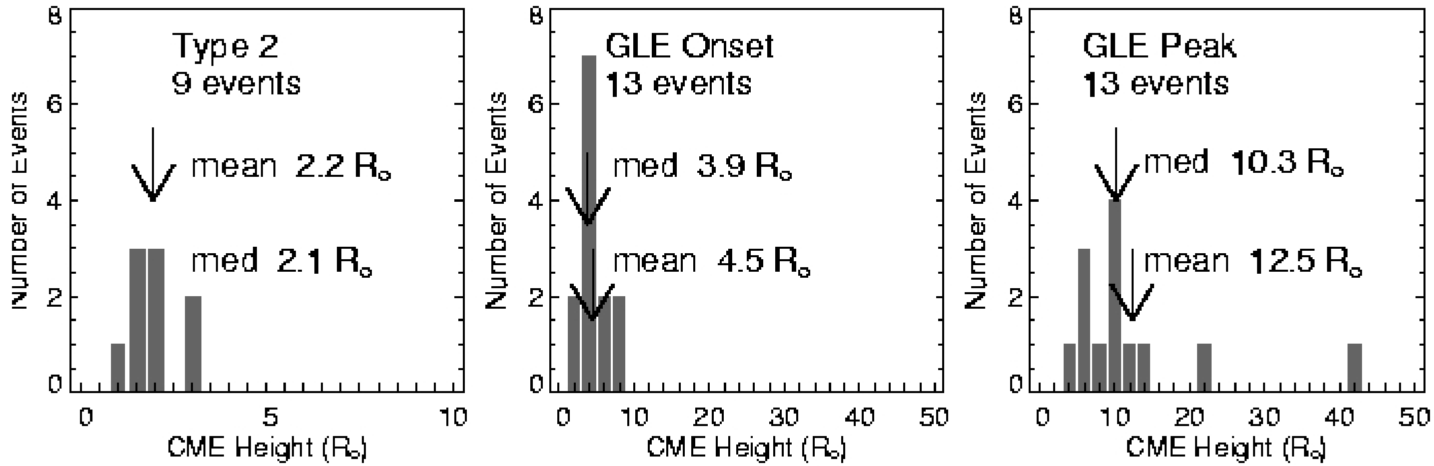
SEP Associated CMEs



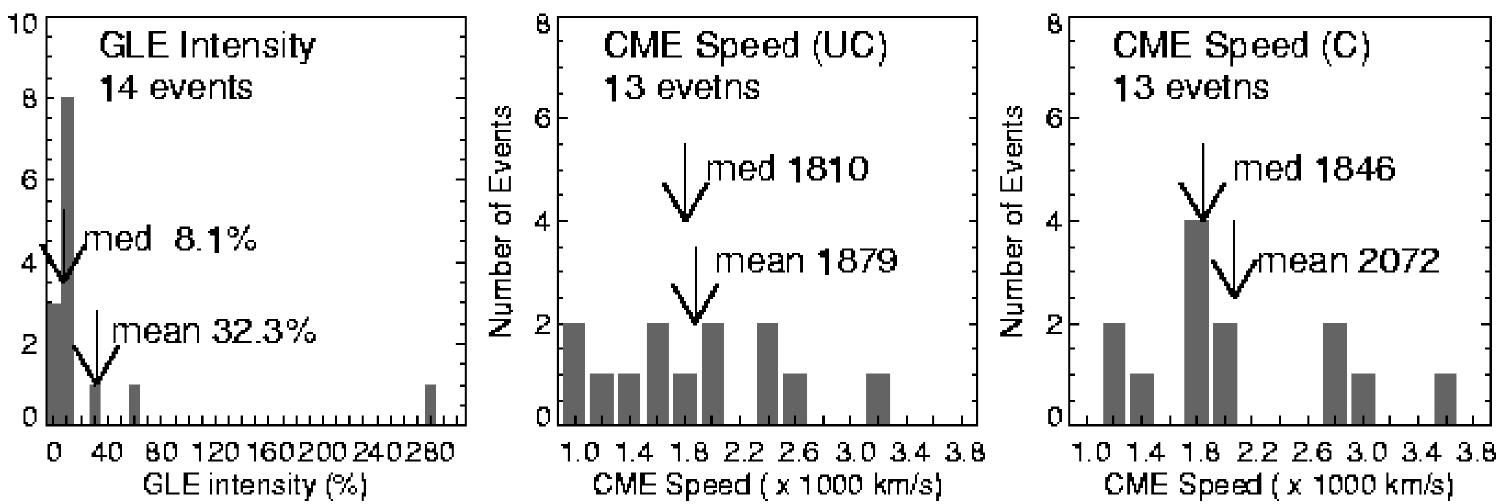
- CMEs have very high speed (Avg ~ 1500 km/s) compared to 480 km/s
- Most CMEs are halos (72%); non-halos are wide (avg ~186 deg) : 45 deg
- Most CMEs decelerating (sign of high speed) – drag: ~0 m/s^2
- Generally western source (Avg ~38 deg); many behind west limb (18%)

CME Height & Speed for GLE Events

Type II present at a lower height: shock present before GLE onset

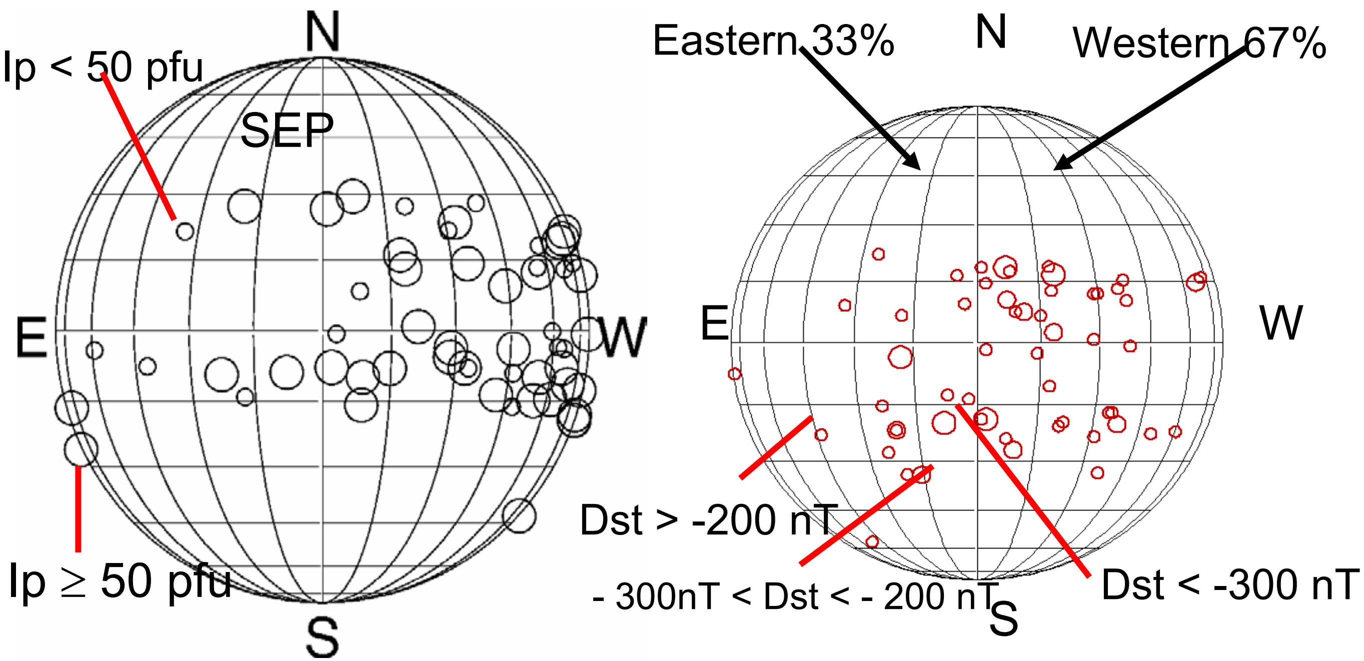


Avg CME speed > 1800 km/s – consistent with SEP events of highest energy



GLEs also shock accelerated

Sources of geoeffective & SEPeffective CMEs



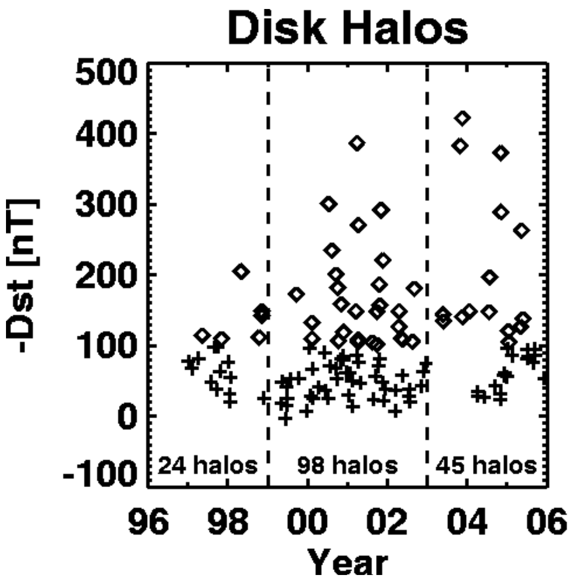
SEPeffective geoeffective

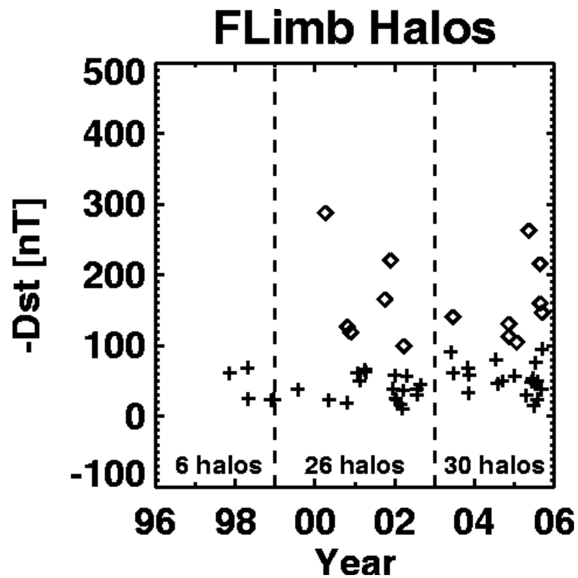
Disk center source for plasma impact; western events for SEPs

Requirement on CMEs for Geoeffectiveness and SEPeffectiveness

Geoeffectiveness	SEPeffectiveness
CME plasma has to reach Earth's magnetosphere (Earth-directed CMEs)	SEPs need to arrive at Earth (Western CMEs)
CME magnetic filed needs to have southward component	Magnetic structure unimportant
CMEs need not drive shocks	CMEs have to drive shocks
Fast CMEs (~1000 km/s)	Ultra-fast (~1500 km/s)

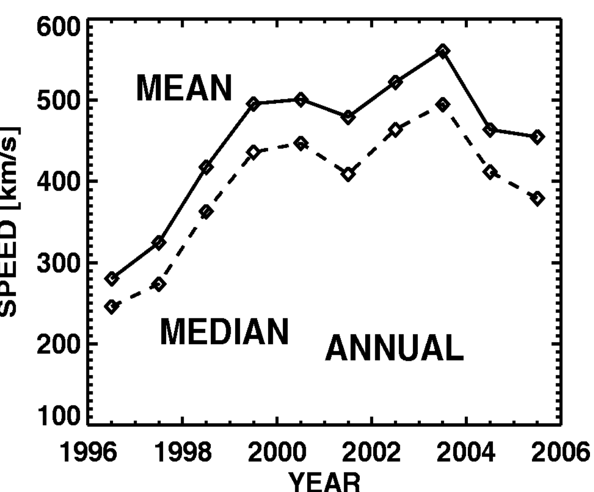
Storms & SEPs at different phases of Solar Cycle

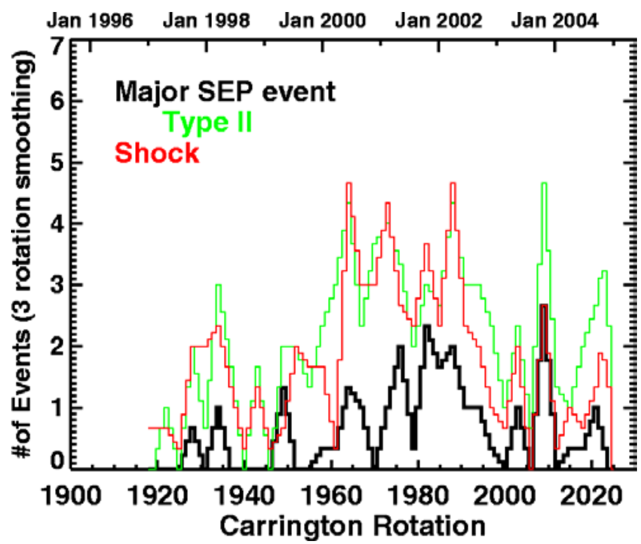




Most storms and SEP events occurred during max and declining phases

The CME mean speed highest during these phases

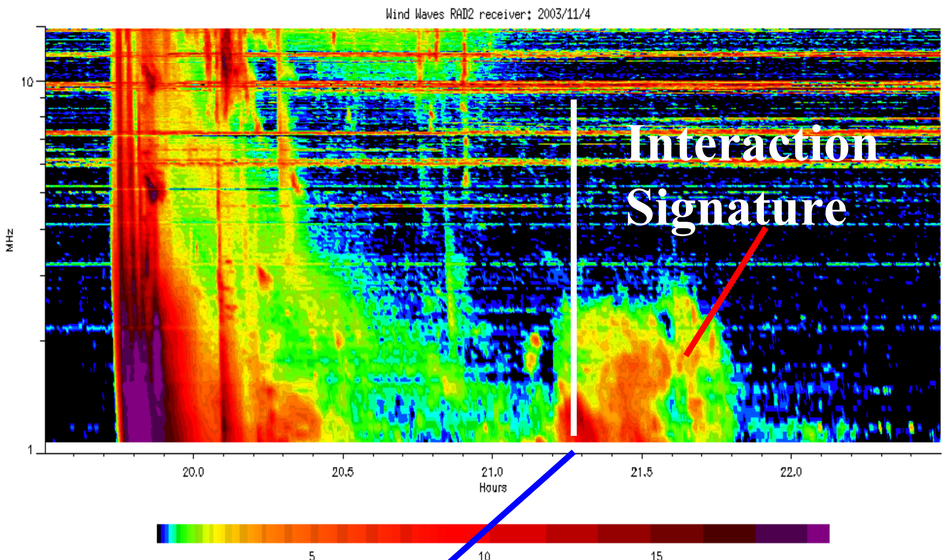




Other considerations

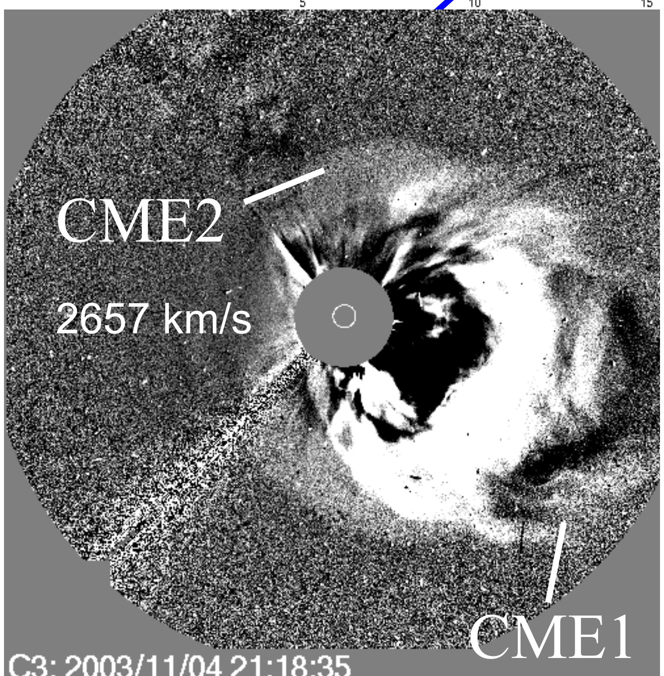
- CME interaction (merging, deflection)
- Interacting events take longer to arrive at Earth (Manoharan et al. 2004)
- Presence of coronal holes nearby
- Ambient medium (density, flow speed)

CME Interaction



Interacting CMEs results in enhanced radio emission in the IP medium → additional electrons accelerated (Gopalswamy et al., 2001ApJL)

SEP-related CMEs seem to be launched into a medium distorted and disturbed by preceding CMEs.

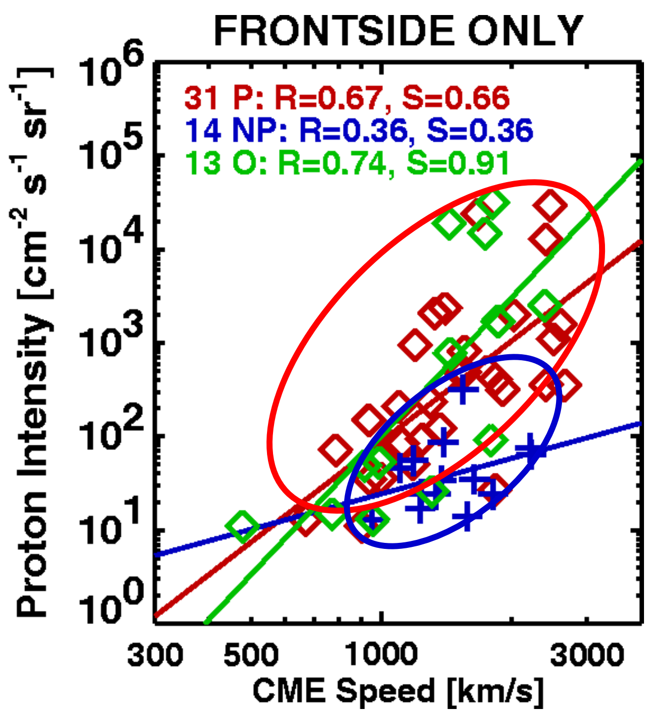


1000 km/s

CMEs with preceding CMEs (P,O) from the same AR result in higher SEP intensity compared to those without (NP).

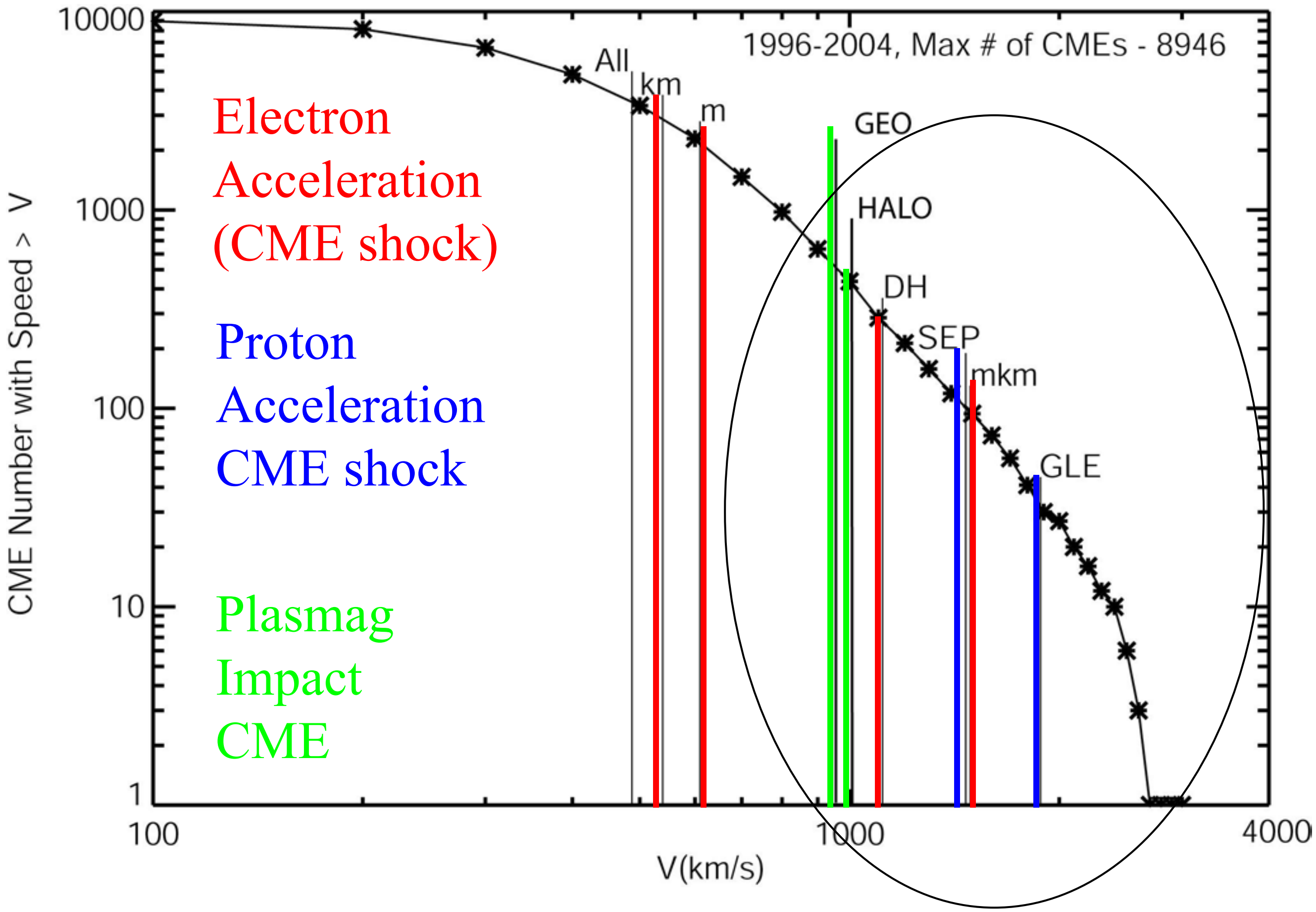
The scatter in the SEP intensity vs. CME speed plot is also reduced when P and NP events are separated

High intensity SEP events are 3 times more likely to be preceded by wide CMEs within a day



Gopalswamy et al. 2004 JGR

Significant CMEs



CMEs of heliospheric consequences V≥1000 km/s

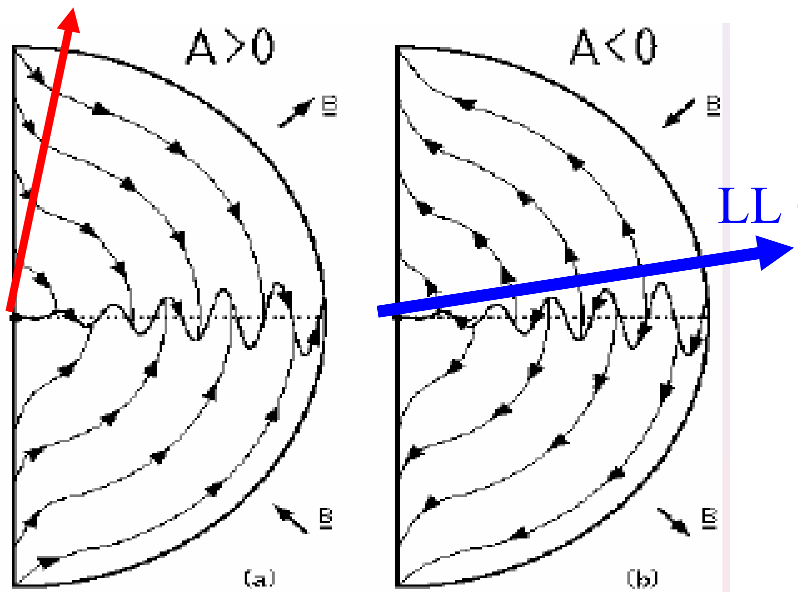
CMEs and GCR Modulation

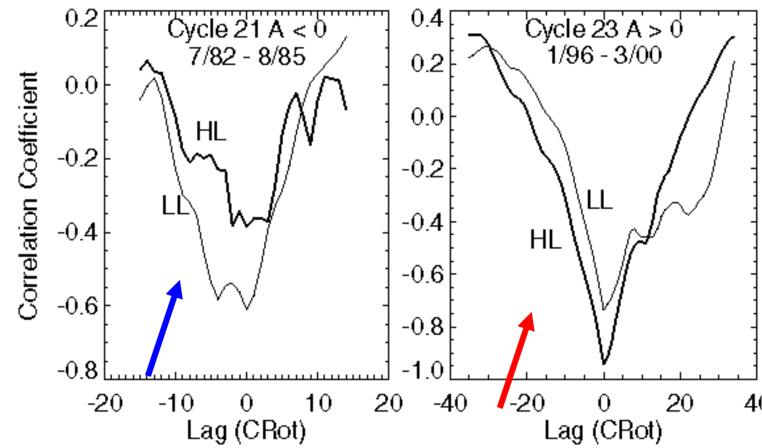
Newkirk, Hundhausen, Pizzo, 1981

CMEs play a role in the modulation of galactic cosmic rays (GCRs). Solar cycle dependent cosmic ray modulation can be explained by the presence of CME-related magnetic inhomogeneities in the heliosphere.

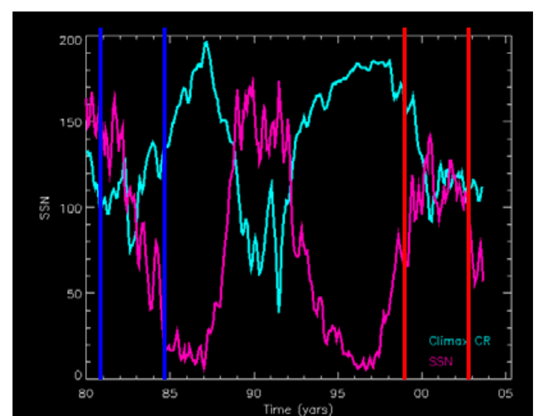
Pre-SOHO:
Rate was not high enough
Min to max variation was too low

CMEs and GCR Modulation

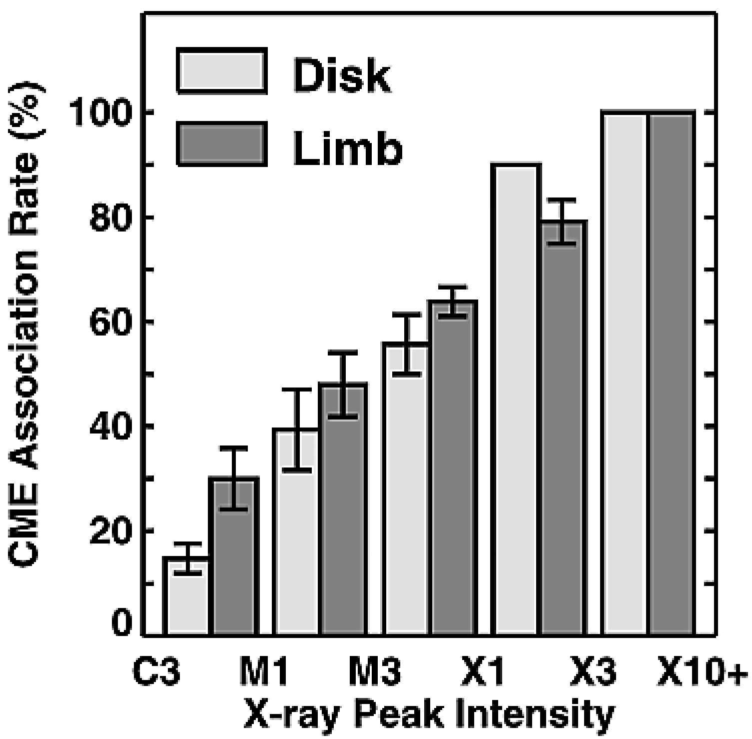




CME rate high enough
Min to max variation high enough
Contribution from High-latitude CMEs



CME-Flare Association



Yashiro et al. 2005 JGR

- The CME association rate clearly increases with
- (1) Flare size (20% for C-class, 49% for M-class and 92% for X-class)
- (2) Longitude of the solar source

- The center-to-limb variation of CME association

- Rate is important only for weak flares

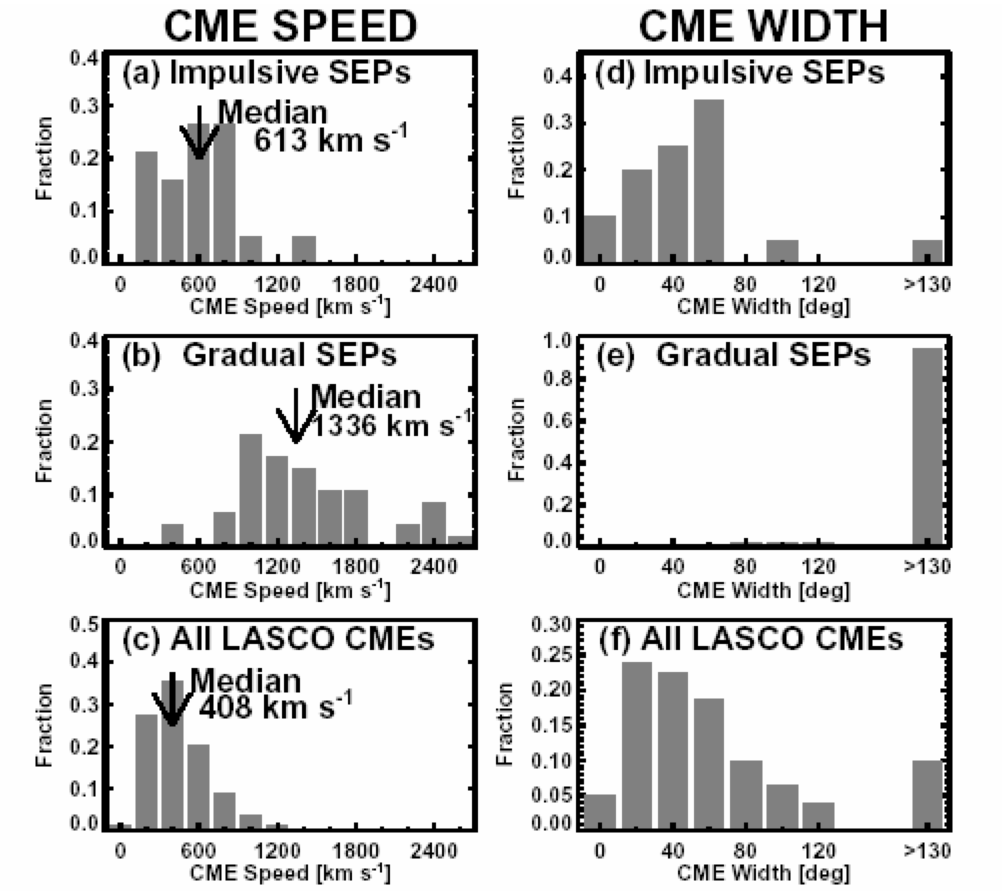
- There are some X-class flares (8%) with no CME association.

- ~20% of CMEs may not have been detected by LASCO

Flare size	0-30 deg	30-60 deg	60-90 deg
X	100	100	100
M	84	100	100
C	50	67	100

Estimated CME Visibility function assuming that all limb CMEs are detected by LASCO

Impulsive SEP Events and CMEs



Impulsive SEP events were thought to be Not associated with CMEs.

Recent study using SOHO data shows that ~40% of the impulsive SEP events are associated with CMEs

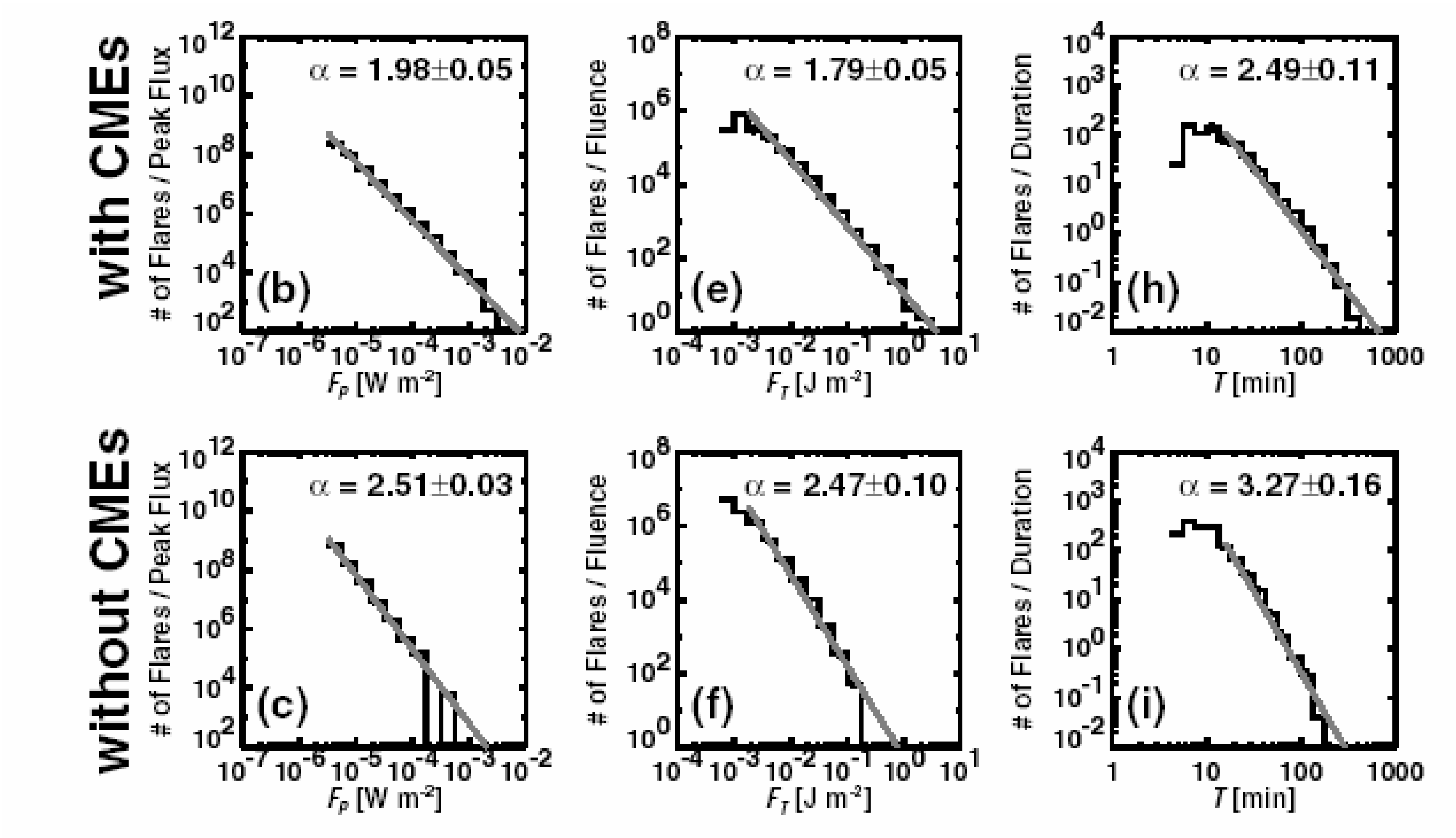
However, the type II burst association is rather poor (~13%)

CMEs associated with impulsive SEP events are slightly faster on the average, but the widths are similar to the general population.

Study based on a small sample (38 events). Needs further investigation

Yashiro et al. 2004

Flares with and without CMEs have different size distributions



Yashiro et al. 2006

Flares without CMEs may heat the corona

- Flare number distributions obey a power-law of the form:
  $dN/dX \propto X^{-\alpha}$
  where X is a flare parameter (e.g. peak SXR flux) and dN is the number of flares recorded within the interval $[X, X+dX]$.
- For flares with CMEs α=1.98±0.05
- For flares without CMEs for the peak flux, α=2.52±0.03
- The larger power-law index for flares without CMEs supports the possibility that nanoflares contribute to coronal heating.
- Flares without CMEs are hotter
- $P \sim \int X\, dN/dX \propto X^{-\alpha+2}$
- $\alpha > 2 \rightarrow$ Small X contribute (Hudson et al. 1991)

Summary

- CME rate increases by an order of magnitude from minimum to maximum: solar max rate a factor of 2 higher than pre-SOHO estimates
- The mean CME speed is higher by a factor of 2 during solar maximum (this was not established before SOHO era).
- ~10% CMEs important for heliospheric impact
- Halo CMEs are faster than average (and wider); ~3% of all CMEs
- All ICMEs are probably Magnetic Clouds
- Geoeffective CMEs form a subset of front-side halos
- Direct CME impact is essential for geoeffectiveness
- Only 1-2% of CMEs are important for SEPs
- Source location and speed differ for Geo- and SEPeffective CMEs
- CMEs may modulate cosmic rays and explain the 22-yr modulation cycle\
- CMEs and flares are closely related
- Flares without CMEs may contribute to coronal heating